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This report deals with the feasibility of using the Space Shuttle to conduct global geomagnetics surveys in support of the global geomagnetic charts published by the Defense Mapping Agency every five years. The study revealed that it is technically feasible and practical to conduct global geomagnetic surveys from the Shuttle.

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**Naval Ocean Research and Development Activity.**
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# Feasibility of Using the Space Shuttle to Conduct Global Geomagnetic Surveys (Phase I—Retrievable Probes).

F. Slade Barker
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# Foreword

The Naval Ocean Research and Development Activity has investigated the feasibility of using the Space Shuttle to conduct global geomagnetic surveys. This survey data is used to construct global geomagnetic models from which the Defense Mapping Agency (DMA) publishes the world magnetic charts of variation and other magnetic information. Magnetic variation information is on nearly all large- to medium-scale charts published by DMA and is vital to general navigation, proper operation of attitude/heading reference system, targeting stand-off weapons, and NAVAIDS, such as VOR, DME, TACAN, and VORTAC. The Navy currently collects geomagnetic data in support of DMA requirements from airborne platforms at an annual cost of $4 million. The operational and political limitations involved in using airborne platforms have resulted in a nonuniform data base in both space and time. Space-borne polar-orbiting surveys overcome both these limitations and provide an instantaneous global snapshot of the geomagnetic field.

**R. P. Onorati, Captain, USN**
**Commanding Officer, NORDA**

# Executive summary

The Naval Ocean Research and Development Activity has studied the feasibility of using the Space Shuttle (Space Transport System) to conduct global geomagnetic surveys in support of the Naval Oceanographic Office requirement to provide the Defense Mapping Agency (DMA) with accurate magnetic navigation information required in constructing the global geomagnetic charts that DMA publishes every five years. This study was funded by the DMA Mapping, Charting, and Geodesy research and development program. The survey accuracy required to support the global charting program is examined, and the practicality and technical feasibility of achieving these accuracies from space-borne missions are discussed. The study revealed that it is technically feasible to conduct global geomagnetic surveys from the Shuttle using a retrievable instrument suite. The measurements must be obtained at least 800 meters away from the Shuttle, which necessitates the deployment of the sensors on a boom, a free-flyer, or a tether. A boom deployment was found to be impractical, while a tethered deployment did not offer enough coverage to support global charting requirements. A free-flyer, which during a given mission would be deployed from and retrieved by the Shuttle for redeployment at a later date, was determined to be the only practical mode of deployment. In particular, the Spartan free-flyer, designed by NASA Goddard Space Flight Center, can easily satisfy all the requirements necessary to support the world charting mission.

The accurate determination of cost involved in such a deployment proved to be the most difficult of all the problems considered. One of the key cost-saving features was the ability to redeploy the same instrument suite, thus amortizing the cost of development over the lifetime of the instrument, which was projected to be 20 years. The cost of fabricating the instrument suite was not nearly as difficult to estimate as the cost of utilizing Shuttle transport services. Even within NASA a large variance in cost estimates is associated with using the Shuttle Transport System. Manifesting the instrument suite as either a secondary or a primary cargo element affects the cost of using the Shuttle Transport System more dramatically than any other cost factor. The philosophy behind the Spartan program was to develop an inexpensive deployer to be the logical extension of sounding rockets; however, if the Spartan is classified as the primary cargo element (occupying approximately one-tenth of the cargo bay and one-tenth of the cargo mass), its transport costs rise to approximately twice that of using a Scout Rocket free launch. The cost of a single Shuttle-launched mission could cost more than the instrument suite development. If, however, the Spartan is classified as a secondary cargo element the cost factors are reduced dramatically.

The possibility of sharing the development cost in deploying the Shuttle-launched instrument suite among those interested in geomagnetic surveys and producing charts was also explored. NASA-Goddard Space Flight Center expressed the belief that if the Navy were to proceed, a Memorandum of Agreement could be worked up between the two agencies whereby they would

split the cost roughly fifty-fifty with the Navy. In addition, the British Geological Survey was also approached on the subject of support. The British Geological Survey, which is responsible for producing the charts published by the British Admiralty, would be—as the Naval Oceanographic Office—prime users of the data produced from such an instrument suite. While large financial support from the United Kingdom is unlikely, a strong possibility exists that the United Kingdom would be interested in providing some of the components used on the instrument suites. An example of such would be the provision of solar panels. The Canadians were also surveyed and appeared willing to contribute a scalar magnetic instrument in the form of a rubidium vapor magnetometer. While the British and Canadian efforts are only minor pieces, they do illustrate the depth of concern about continuing global geomagnetic surveys from space.

# Acknowledgments

The Shuttle-based global geomagnetic vector surveys feasibility study has been funded through Program Element 63701B by DMA/STT under the program management of CDR Jeff Bodie.

Appreciation is expressed to Dr. W. Webster of NASA/GSFC for his attention to many of the technical problems. Special appreciation is also expressed to CAPT J. M. Sears of NAVOCEANO, Dr. J. W. Moore of NASA/HQ, and Dr. L. S. Nicholson of NASA/JSC for their help in establishing cost baselines. I also thank the U.S. Air Force Geophysical Laboratory and the American Geophysical Union for permission to use various illustrations. I especially thank Mr. R.H.Higgs of NAVOCEANO and Drs. D. L. Durham and J. W. Caruthers of NORDA for their continued interest and support.

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# Feasibility of using the Space Shuttle to conduct global geomagnetic surveys

## (Phase I—Retrievable Probes)

## Background

Magnetic declination has always played a primary role in naval navigation and the opening of the New World to the European colonial powers. Today, many inertial navigation systems use declination measurements to initiate and update heading references and, in the event of gyro malfunction, also serve as primary heading references. While air navigation has expanded the requirement for accurate declination information from the ocean scale to a truly global scale, the naval powers of the world have historically been responsible for providing accurate declination information.

The first magnetic ocean survey was conducted by Sir Edmund Halley in the Atlantic Ocean during 1698–1700 on the sailing vessel, PARAMOUR PINK, and resulted in the publication of the first oceanographic variation charts. In the United States, the Carnegie Institute of Washington's Department of Terrestrial Magnetism undertook a world magnetic survey between the years of 1905 and 1938. The United States Hydrographic Office published the results of these surveys as global magnetic variation charts. The ocean surveys were conducted from three ships: the GALILEE, the CARNEGIE and the GEORGE B. CLUEPT. The world survey was terminated when the CARNEGIE blew up and was destroyed.

At the close of World War II the Department of Terrestrial Magnetism alerted various U.S. Government agencies that their interest in the magnetic field had changed from charting to scientific, and that they would no longer be in a position to provide data from which to produce declination charts. As a result, the concerned agencies met to determine their respective responsibilities. Consequently, a Memorandum of Understanding was signed between the U.S. Coast and Geodetic Survey and the U.S. Naval Hydrographic Office in which the U.S. Geodetic Survey would offer help when requested by the Hydrographic Office to make measurements, to analyze the measurements, to train personnel, and to produce charts.

The Navy-initiated Project MAGNET was a worldwide vector survey program to gather the measurements required for producing these charts. During the same period, the English Government requested financial assistance from the United States to complete construction of the non-magnetic vessel, RESEARCH. Dr. Aldridge of the Naval Ordnance Laboratory noted at that time that surveys could be carried out more efficiently with airborne instrumentation than with shipborne instrumentation. He advised that the Navy proceed to execute Project MAGNET with an airborne platform rather than a marine platform. Since then, Project MAGNET has been one of the most successful geomagnetic vector airborne data programs ever to be executed.

In the fall of 1979 the National Aeronautics and Space Administration launched MAGSAT, a satellite to measure the vector magnetic field of the earth. This program has successfully demonstrated that measurements applicable to a world charting mission can be made from space. In addition, it also demonstrated that the lack of true global data has induced errors in the variation charts over many strategic areas. These differences are illustrated in Figure 1, which shows the dissimilarities between the International Geomagnetic Reference Field Epoch 1980 and the World Chart Magnetic Model Epoch 1980. The International Geomagnetic Reference Field for Epoch 1980 was generated solely from the MAGSAT data, whereas the World Chart Magnetic Model Epoch 1980 was generated from Project MAGNET data and various land data to produce the Epoch 1980 variation charts.

Clearly, Project MAGNET now stands at the crossroads concerning which sort of platform will be required to execute their data collection in the future. The same arguments used by Dr. Aldridge in 1948 for an air magnetic platform versus a marine platform can now be applied to argue for a space platform versus an aeromagnetic platform.

## Data effectiveness

The geomagnetic field varies in both time and space. The time variation requires a constant survey effort to maintain accurate variation charts, which are published every five years. Two major complications exist when using aeromagnetic surveys to update the data base. Many areas of strategic interest are politically denied access to the Project MAGNET aircraft survey platform, and the number of these areas has grown rapidly since the early 1950s.

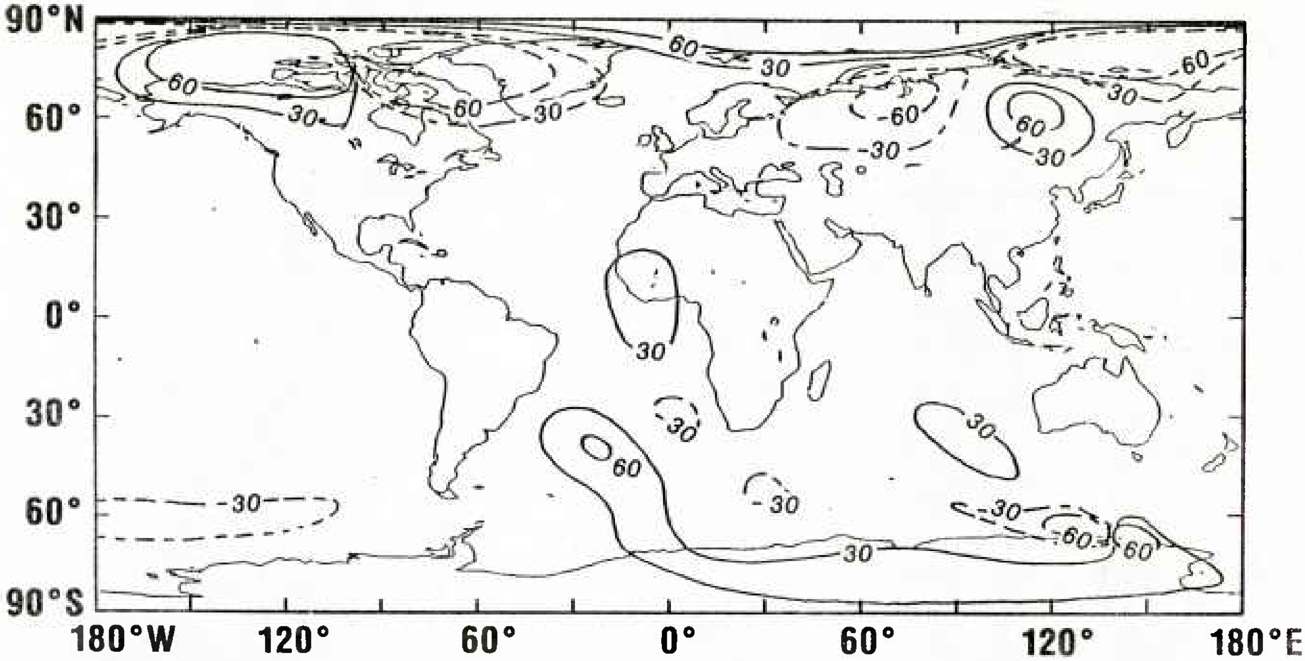

*Figure 1. Difference between IGRF 1980 and WC80*

In addition to the spatial limitations, temporal limitations exist. Project MAGNET presently has only one dedicated aircraft conducting aeromagnetic surveys in support of world charting. The data collection rate is slow when compared to the secular change rate of the magnetic field. Thus, before a chart can be compiled the survey data must be reduced to a common epoch. This compilation results in a limited coverage of the spatial domain, which is constantly degraded by the temporal variations in the field. Space-borne surveys can totally eliminate the problem of nonuniform global coverage and any ambiguities that result from temporal variations. True global coverage can be obtained quite easily by using polar orbits. A few day's worth of data will suffice to provide an adequate data base for charting purposes. The secular change in the geomagnetic field varies at periods from a few years to centuries; thus, data collected over a few days is, in effect, collected in an instant of time when compared to the typical periods of secular variation. Space-borne geomagnetic surveys offer true global coverage that is instantaneous with respect to secular variation, something aeromagnetic surveys will probably never be able to offer.

Figure 1 also illustrates error sources due to both lack of spatial coverage and lack of adequate temporal update. While numerable airborne data exists about the anomaly off the Ivory Coast of Africa, this data is spread through time, which illustrates the effects of poor temporal control.

The declination anomalies observed over a large part of the USSR are due to a lack of data in that area.

Until the MAGSAT data were analyzed, some doubts were expressed as to the validity of applying space data to surface analysis. Figure 2 illustrates some typical ground data flown by Project MAGNET to ground truth MAGSAT. It can be seen that the ground truth is easily within the one-half degree specifications of the charting requirements and is within the resolution limit of the Project MAGNET aircraft. Independent analysis of the MAGSAT data was conducted by N. P. Ben'Kova et al. (v. 23, n. 1), and published in the *Soviet Journal of Geomagnetism and Aeronomy*. They found that "the MAGSAT model approximates better than any of the previous models the experimental ground and near-earth data and represents the main geomagnetic field completely." Further, it was found that MAGSAT data analysis could be conducted at a much higher modeled degree and order than normally used for charting purposes.

In summary, it appears that not only are satellite data applicable for world charting purposes and for representing the geomagnetic field at the surface, but they also have the distinct advantage of offering instantaneous global coverage.

## Accuracy requirements

Accuracy requirements for the models from which the variation charts are generated are summarized in a Defense Mapping Agency Headquarters letter dated 31 December 1980. "The accuracy goal of the model is better than half a degree based primarily on the inherent accuracy

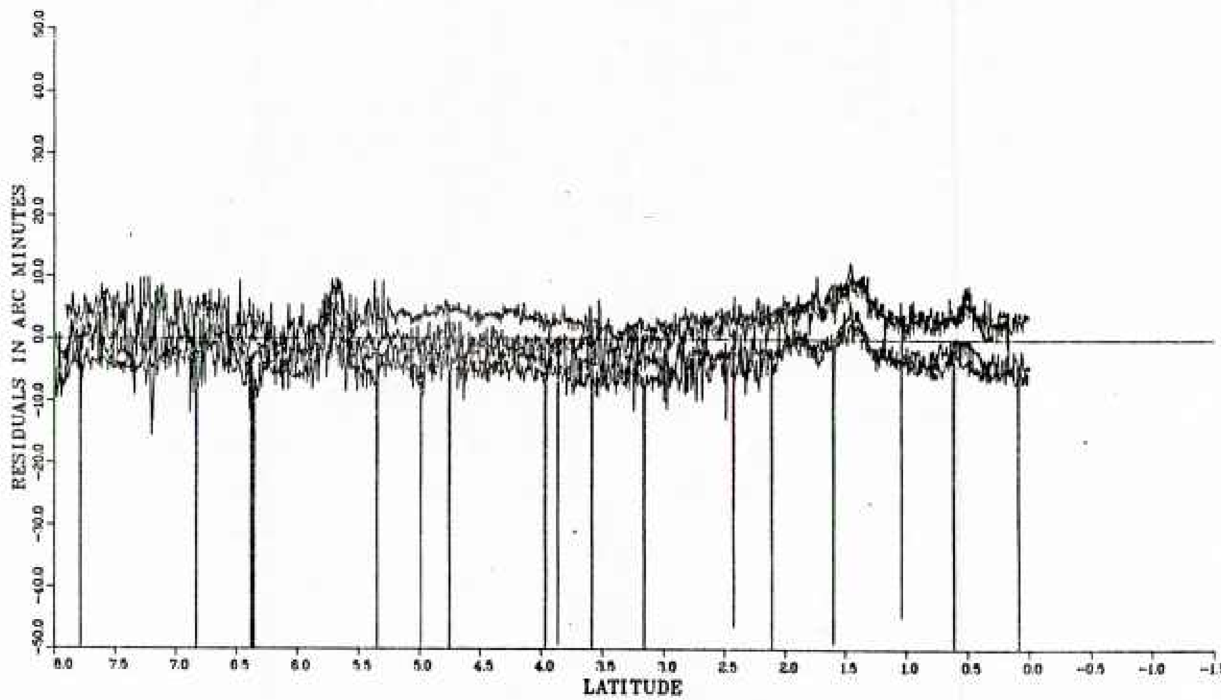


*Figure 2. Observed declination from flight 1067 at 18°W minus Goddard Space Flight Center Model 9–80.*

of avionic systems and the accuracy and initialization requirements of strategic backup and tactical navigation systems.'' In practice, however, a lower limit of resolution of approximately two-tenths of a degree exists. This limit is imposed by the daily variation of the magnetic field which, depending upon the geomagnetic latitude, can cause a variation measurement taken at any given time of day to vary by approximately two-tenths of that of the average variation during that day. The ability to obtain resolution of much greater accuracy is redundant.

The existence of a limit for the pragmatic use of variation data has a profound implication on how a survey is designed and executed. A survey of general scientific interest requires data accuracy and resolution of a much higher degree than necessary for the pragmatic use of charting. To illustrate this point we examined the analysis of MAGSAT data.

The MAGSAT data consisted of magnetic measurements, measurements of spacecraft orbital position, and measurements of spacecraft's attitude. The attitude of the MAGSAT spacecraft was determined by using horizon scanners, a sun sensor, star cameras, and gyroscopes. Of these, the star camera gave the most precise attitude information, but required the greatest amount of investment and the greatest amount of data reduction effort. The gyros were the least accurate and were used to fill in gaps between direct measurements made of the sun, the horizon, or the stars. The sun sensor and the horizon scanners were initially used to give a rough approximation of the attitude. The data that were reduced using these two sensors gave what was referred to as course attitude MAGSAT data. Because these data were zero biased and random, the great redundancy inherent in satellite data allowed statistical modeling of this data to much higher accuracies than the inherent resolution of either the sun sensor or the horizon scanner. Models prepared from the course attitude data, when compared with models prepared from the fine attitude data (see Table 1) that incorporated star camera measurements, show that the difference in the computed declination rarely exceeded 1 minute of arc anywhere over the earth's surface, with the obvious exception being the neighborhood of the dip pole. These models were produced from essentially two day's worth of data (6–7 November 1979). The models compared were Goddard Space Flight Center Model 3 and Goddard Space Flight Center Model 9, which represent the course and fine attitude data, respectively.

The implication of the described exercise is that for charting purposes, most likely star cameras are not needed, which reduces the cost of the instrument suite by at least several million dollars. It should be noted, however, that for accurate scientific investigations, fine attitude determinations would be required and that this is one of the major differences between designing a survey for scientific

Table 1. Attitude requirements.

A comparison of the geomagnetic field models produced by MAGSAT data of 6–7 November 1979 using coarse attitude and fine attitude data indicates that errors in the coarse attitude data were zero biased and noncorrelated with respect to the fine attitude data. Further, the differences in variation (declination) produced by these two models is on the order of one arc minute globally, with the exception of areas in proximity to the dip poles.

Residuals (Coarse Data—Coarse Model)

| Vector Element | Av | Sig | RMS |
|---|---|---|---|
| North | 10 nT | 55 nT | 56 nT |
| East | 84 nT | 97 nT | 128 nT |
| Vertical | 22 nT | 52 nT | 56 nT |

Residuals (Fine Data—Fine Model)

| Vector Element | Av | Sig | RMS |
|---|---|---|---|
| North | −0.1 nT | 7.6 nT | 7.6 nT |
| East | 0.5 nT | 7.4 nT | 7.4 nT |
| Vertical | 2.5 nT | 6.5 nT | 7.0 nT |

Residuals (Coarse Model—Fine Model) (averaged over the sphere)

| Vector Element | Av | Sig | RMS |
|---|---|---|---|
| North | 5.3 nT | 14.9 nT | 15.9 nT |
| East | 0.0 nT | 9.5 nT | 9.5 nT |
| Vertical | 0.1 nT | 22.9 nT | 22.9 nT |

| | |
|---|---|
| Average difference in model coefficients | 0.014 nT |
| RMS difference in model coefficients | 1.0 nT |

Conclusion

Attitude of the quality produced by the horizon scanner, coupled with the sun sensor on MAGSAT, is sufficient for DoD world charting/modeling requirements.

investigation versus the pragmatic utility of chart production.

The magnetic sensors required of the space-borne instrument suite to support world charting would consist of a triaxial, mutually orthogonal fluxgate magnetometer and an absolute scalar magnetometer to check the fluxgates drift. While space-ready, triaxial fluxgate magnetometers are not an off-the-shelf item, their design concepts are well understood. Their resolution of less than 1 nanotesla (nT) per axis is more than adequate for charting purposes. Such resolution of magnetic vector components implies approximately 10 arcs/second resolution in the magnetic vector.

To better determine the positioning accuracies required, the along-track gradient and the cross-track gradients in the vertical component of a typical polar orbit were computed from the international geomagnetic reference field model. Vertical field was chosen for this study because it experiences the largest gradients both along and cross track. These gradients are shown in Figure 3. A 2/10° error in a 30,000 nT field would result in an error of 104 nT. An examination of Figure 3 illustrates that a positioning accuracy of 1/2 km would most likely be adequate for world charting purposes.

In summary, the magnetometer suite such as used on MAGSAT is more than adequate. Combining the basic MAGSAT magnetic instrumentation with an orbital positioning of approximately 500 m and the attitude determination derived from sun sensors, horizon scanners, and gyros would provide an instrument suite adequate for world charting modeling purposes.

## Shuttle magnetic environment and modes of deployment

When conducting magnetic surveys, consideration must always be given to the magnetic properties of the survey platform. The Shuttle, along with its cargo manifest, constitutes one type of error source. In addition to the static magnetic fields, dynamic magnetic fields are set up by currents flowing within the Shuttle. These currents are set up by power sources, computers, command and response activities, etc. Another type of magnetic interference is caused by the dynamic interaction between the Shuttle and the ionosphere through which it flies.

The first two noise sources, the static and dynamic magnetic emissions of the shuttle, dictate that the magnetic sensors must be removed about 800 m from the neighborhood of the Shuttle. There are three ways of moving the magnetic sensors away from the Shuttle: the sensors could be mounted on a boom, placed on a tether, or put upon a free-flyer that would be launched when the Shuttle reaches station and be retrieved before the Shuttle re-enters. The relative effectiveness of each method depends upon the distance of separation required. The third noise source, dynamic movement of the Shuttle through the ionosphere, forms an anomalous plasma sheath, which is shock-bounded with a characteristic teardrop shape about the Shuttle. Currents flowing over the boundary and through this plasma sheath require that the measurements be made beyond the sheath. While the extent of the plasma sheath has not been conventionally measured, evidence of its existence was found on Space Transport System (STS) 3. An estimated enhancement of the ambient plasma about the Shuttle by a factor of 30 was observed by Covault (Aviation Week and Space Technology, v. 116, 74–81) from a combination of observed optical emissions and direct measurements using the plasma diagnostic package. It was also observed that this anomalous plasma nearly vanished at night. There is no direct evidence on the extent of the plasma sheath, but based on high-frequency (HF) reflection studies, the sheath is probably near 400 m in the

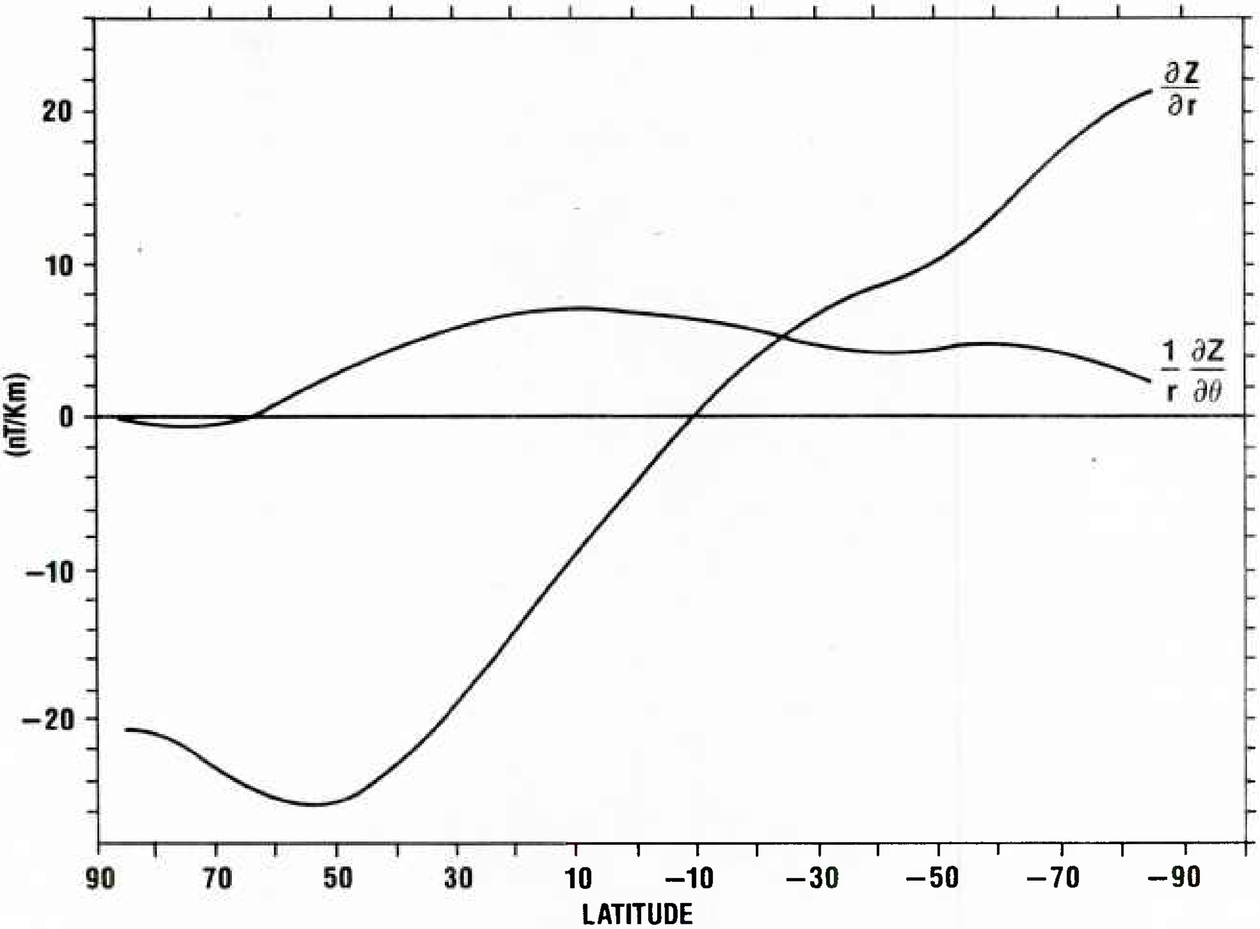


*Figure 3. Cross track gradient in Z along track gradient in Z.*

forward direction and 1-1/2 km in the aft direction. The Johnson Space Center's STS payload accommodation manual sets the design specification for the Shuttle direct current (DC) fields not to exceed 160 dB above 1 picotesla (pT). When this criteria is combined with the indirect measurements of the plasma diagnostic measurement package, it can be inferred that at least 800 m separation is required between the magnetic sensor and the STS in any direction except aft of the STS velocity vector.

The cost of developing an 800-m boom to deploy the sensors from the STS would probably exceed all other costs in developing, producing, and transporting the magnetometer instrument suite (F. F. Mobley, Johns Hopkins Applied Physics Laboratory, personal communication).

Currently, Italy and the United States are involved in a joint effort to develop a tethered subsatellite system to be deployed from the Shuttle. Applicability of such a system to deploy the magnetic instrument suite was examined. The associated support equipment and safety regulations required to support a tether effort are complex and costly. Second, the ground turnaround period for the tether is projected to be 18 months, which is too infrequent. In addition, care must be taken to avoid a conducting tether and, to date, only one deployment of a nonconducting tether is scheduled. Both the tether and the boom severely restrict the maneuverability of both the STS and the cargo manifest. Maximum on-station time of a tethered subsatellite system is anticipated to have a duration of only 36 hours. Thus, neither a tethered subsatellite system nor a boom deployment appear to be a feasible means of deploying magnetic sensors for world charting purposes.

A free-flying mode of deploying a magnetic instrument suite from the Shuttle appears to be the only feasible way of conducting an ongoing Shuttle-based geomagnetic global survey. The development of a Shuttle-deployed and retrievable free-flyer has been underway for some time at the NASA Goddard Space Flight Center. The free-flyer, called the Spartan, was initially conceived to augment the sounding rocket program within NASA. Accordingly, the philosophy was to provide users of the Spartan cheap access to space experiments with 40- to 90-hour durations.

A contract was let with Goddard Space Flight Center to study the feasibility of adapting the Spartan to do magnetic surveys. At least three Spartan missions have been identified and are presently being configured. All three missions are being flown for the Naval Research Laboratory and are involved in solar physics and astronomical investigations. These platforms are already configured for attitude determination and stabilization using sun sensors, gyroscopes, and cold gas thrusters. They maintain their own power source and have their own data recording capabilities. The NASA Spartan carrier is presently designed to be deployed and operated from the Space Shuttle as an autonomous subsatellite. Upon mission completion the Spartan will be retrieved by the Shuttle and returned to the ground for maintenance and re-use. The Spartan program seems ideally suited to Project MAGNET's requirements.

## Orbital characteristics implications and deployment frequency

The Spartan cannot change its orbital parameters on its own. Therefore, the orbital altitude and inclination of the Spartan is identical to that of the STS upon the Spartan's deployment. It is anticipated that the majority of Spartan deployments will be made at an altitude of approximately 220 km. This altitude would place the Spartan between the F-1 and the F-2 layers of the ionosphere. Inasmuch as no sun-synchronous orbits are scheduled for the STS, all the Spartan deployments would fly in day and night meridians. By contrast, MAGSAT was designed to fly in a near-polar orbit in the dawn-dusk meridian and at an altitude between 500 and 350 km. This pattern was flown to place MAGSAT in what was thought to be a quieter part of the ionosphere, both spatially and temporally.

While the ionosphere may be in varying states of excitation at any given instant of time, it does maintain distinct daily variations. These variations in ion density are caused primarily from the sun's ionizing effects on the ionosphere. Figure 4 illustrates the change of ion density with orbital altitude of a satellite that was flown in the dawn-dusk meridian. These data were collected by the Air Force Geophysical Research Laboratory, Cambridge, Massachusetts. The solid curve of Figure 5 represents the ion density obtained from a sounding rocket experiment flown from Cape Kennedy at night and the dotted curve represents the ion densities scaled off Figure 4 and plotted as a function of altitude. The top two horizontal lines of Figure 5 represent the orbital altitude limits of MAGSAT. The bottom horizontal line represents the probable orbital altitude of the Spartan Carrier. Figure 5 illustrates that in the nighttime ionosphere, the Spartan is less likely to penetrate ion densities as heavily as experienced by MAGSAT by at least an order of magnitude. This sharp attenuation of ion density at night is a manifestation of the ionization reduction in the F-1 layer and in the general dissipation of the E and D layers from the ionosphere that take place only at night. This phenomenon is also confirmed by the fact that the plasma density anomalies observed about STS nearly disappeared at night. The fact that the MAGSAT data base was more than suitable for world charting purposes illustrates that such high ion densities are not detrimental to conducting magnetic surveys at altitudes of the STS orbit.

Magnetic activity at any given time is quite variable. There are times when the magnetic field is quiescent and times when it is disturbed. Because satellite data collection proceeds so rapidly, the high-frequency magnetic disturbances may alias as a geologic signal. Magnetic storms cannot be predicted in advance of the Shuttle manifest schedules. Therefore, adequate redundancy of surveys must be designed between chart epochs such that data collection during quiescent periods is assured. This variation problem is why the long turnaround time and limited time on-station make the tether of limited use. Figure 6 illustrates magnetic activity for 1977. Data that can easily be adapted for charting and modeling purposes can be collected at any time the Kp level is less than 2+. While the particular magnetic activity for a given year will not be repeated, its bulk properties are roughly periodic. Because the magnetic activity is highly correlated with the solar cycle years, indices approximately 11 years apart share the same statistical properties of quiet and disturbed days. The year 1977 was chosen to illustrate what might be expected if a launch were to take place in 1988. Table 2 computes the probabilities of obtaining quiet-time data based on the number of surveys done in a given five-year period. The results indicate that if surveys are flown at an average rate of two per year for a duration of four days each, then the probability of obtaining adequate quiet time data within a charting epoch period of five years is above 95%.

The Spartan carrier orbit is dependent upon the orbit of the STS. The majority of STS orbits are planned to be nonpolar and to range from 28.5° inclination to approximately 56° inclination. Planned polar projections from Vandenburg Air Force Base will begin in 1986. It is probably unreasonable to assume that each deployment of the Spartan magnetometer mission would be deployed in a

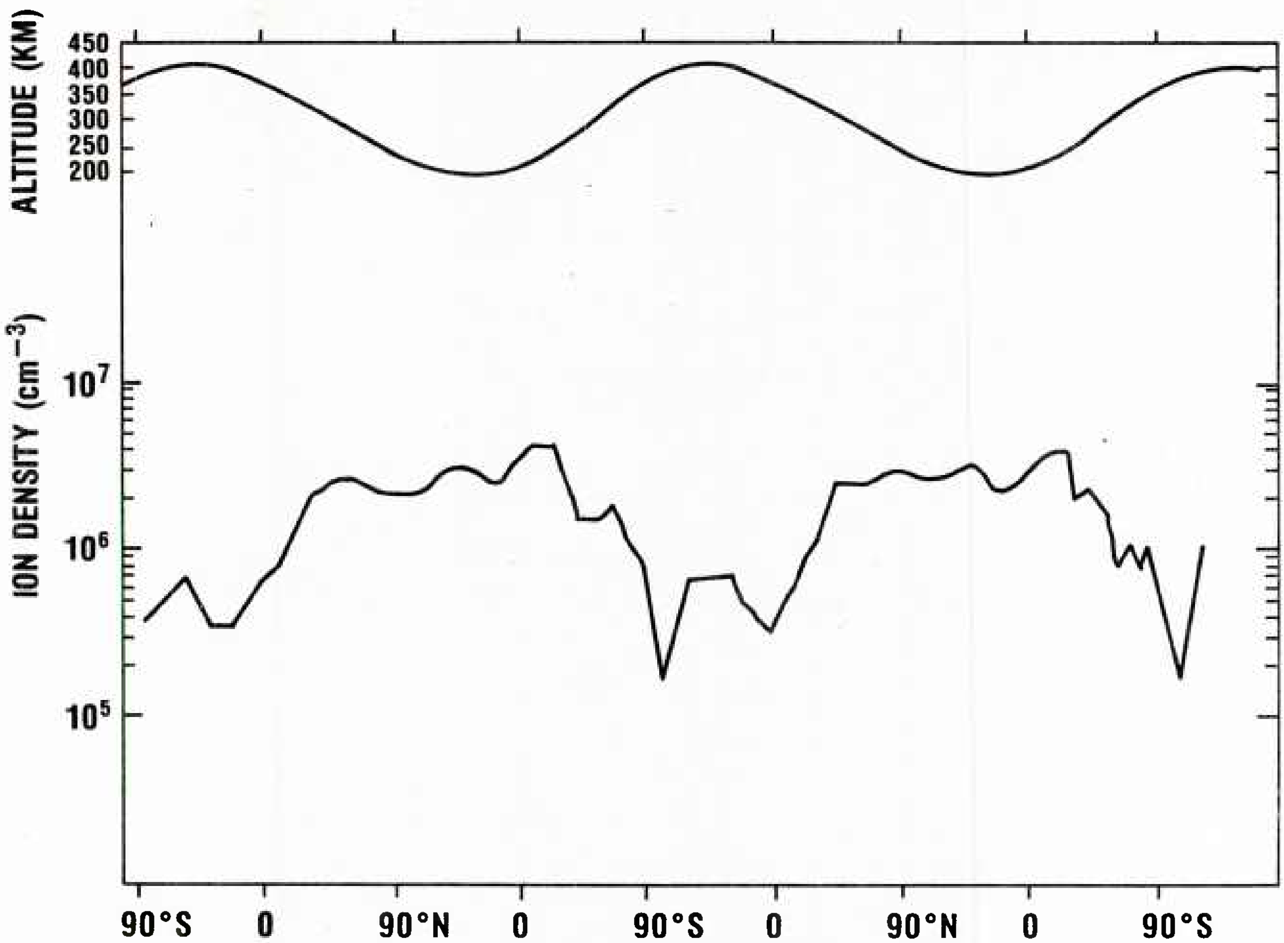


*Figure 4. Change of ion density with altitude in dawn-dusk meridian.*

polar orbit; however, many advantages can be achieved from a mixed orbit scenario. Such a mixture of orbital inclinations in the data base allows for the possibility of using cross tracked data to adjust data collected during magnetically active times.

## Data reduction

Data reduction problems fall in two broad categories. The first category involves the survey observations, which include observations made directly on the survey platform and observations made of the survey platform, particularly when ground tracking is involved. Data reduction problems of the second category involved reducing the observations with respect to other independently obtained geomagnetic data.

The data collected from the Spartan will, of course, be coded and be in the Spartan coordinate system. These data must first be decoded and then rotated from the Spartan coordinate system into an earth time-space coordinate system. While designing the encoding and decoding routines is difficult and is a project in its own right, this problem should not impact on the feasibility of using the Shuttle to conduct geomagnetic surveys, inasmuch as the general problem has been solved for other operational missions.

While spherical harmonic analysis may be applied to the data at this stage, it is advisable to use independent geomagnetic data to help separate external from internal sources in the measured data. The primary external source that influences the observations is caused by a ring current flowing at a distance of several earth radii from the surface. The current density and direction of this source can vary dramatically with time. While one can theoretically separate the external from the internal sources through harmonic analysis, the ring current variability is short compared to the time required to collect enough data for an adequate harmonic analysis and thus becomes difficult to separate. The ring current activity, however, can be easily monitored from select observatories about the magnetic

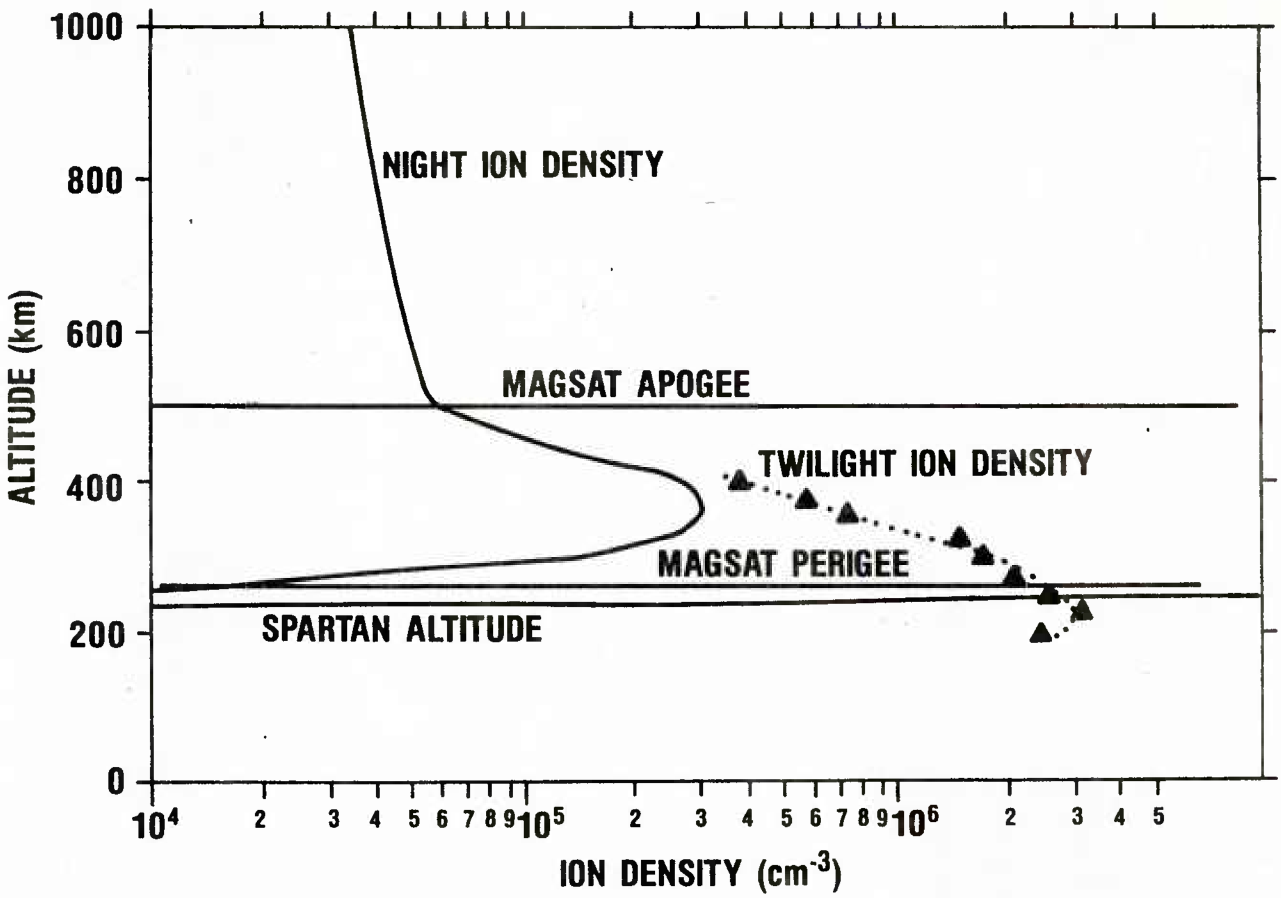


*Figure 5. Ion density.*

equator. The measure of the ring current activity is the Dst index. M. Sugiura, NASA Goddard Space Flight Center, demonstrated the use of this type of analysis in correcting MAGSAT data for Dst errors. In view of the fact that a given STS Spartan mission might have a duration of only four days and that the probability of collecting quiet time data on any one mission is only 25%, it would appear desirable to be able to use magnetic observatory data to correct spaceborne observations during magnetically active periods caused by ionospheric disturbances, as well as Dst. At present, no such techniques have been developed for the broad range of disturbances. The redundancy inherent in the prolonged MAGSAT survey ensured the inclusion of quiet-time data even during one of the most magnetically active years. If a Shuttle-deployed magnetic survey were to be embarked upon, then it would seem advisable to develop such data reduction techniques. Such a program of research could use presently available MAGSAT data collected during magnetically active times and correlate it with data collected by observatories during the same time.

## Required Spartan modification

The present Spartan carrier configuration is presented in Table 3. To adapt the Spartan carrier to perform geomagnetic surveys of four or more days duration, specific modifications must be implemented. These modifications include increasing mission life, shielding and compensating for its magnetic contamination, and including some form of tracking device. The results of these studies, which were subcontracted by NASA Goddard to Operations Research Inc. (ORI), are published in ORI's Technical Report No. 2354 and No. 2356. These reports are included as Appendices A and B to this report.

Increasing the mission life of the Spartan carrier involves modifications to the subsystems for data recording, attitude control, and power. An increase in mission life implies an increase in the amount of data collected, which necessitates either increasing the data recording capability or developing routines to pack the data. Other alternatives, such as bubble memory, optical disk storage and

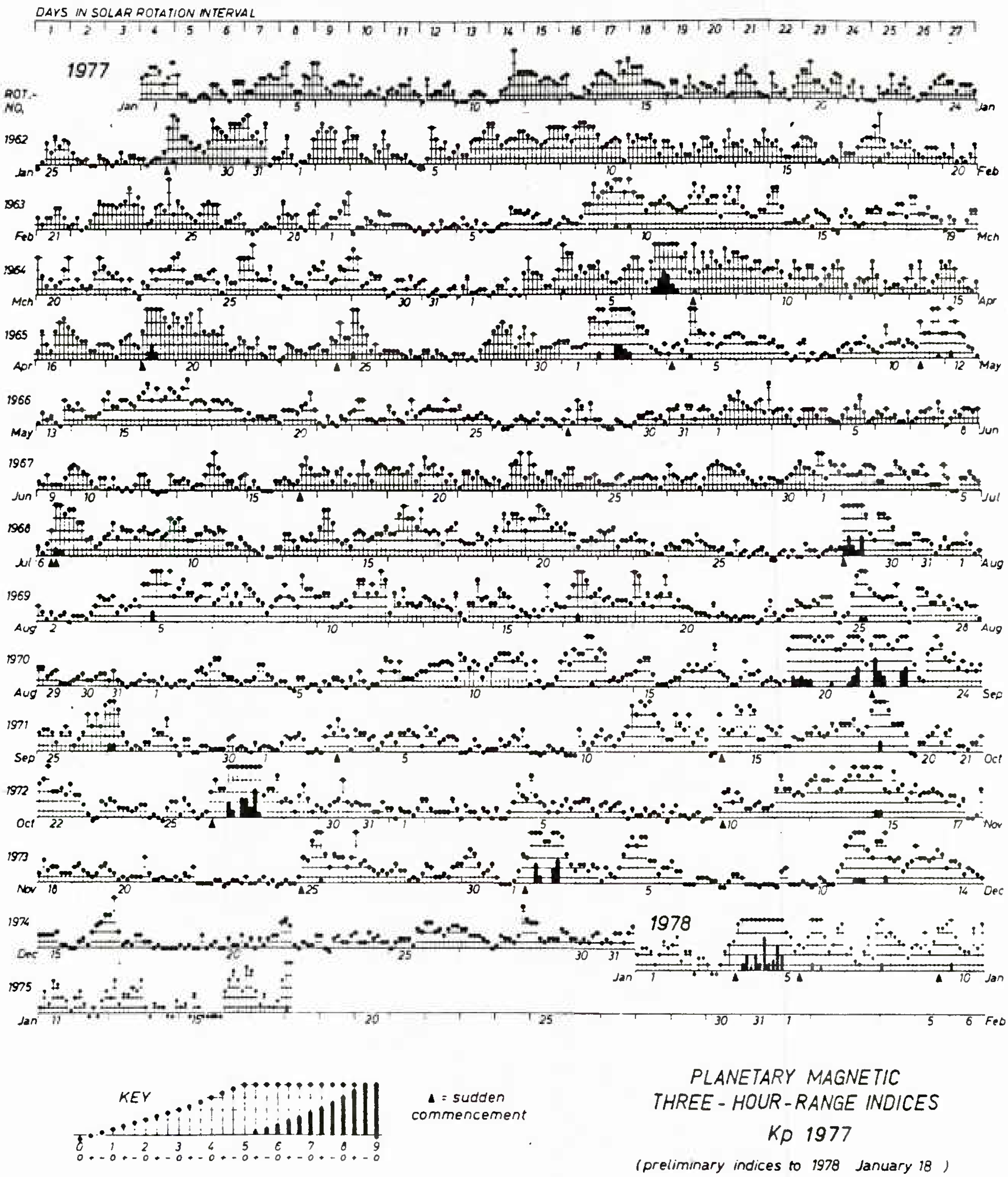


*Figure 6. Planetary magnetic three-hour-range indices.*

Table 2. Probability of obtaining a magnetic quiet time survey.

The following probability of obtaining data during extremely quiet magnetic conditions between chart production epochs is based upon the assumption that such conditions will occur about 25% of the time.

| Number of missions, between chart epochs | % probability of getting quiet data |
|---|---|
| 1 | 25 |
| 2 | 44 |
| 3 | 58 |
| 4 | 68 |
| 5 | 76 |
| 6 | 82 |
| 7 | 87 |
| 8 | 90 |
| 9 | 92 |
| 10 | 94 |
| 11 | 96 |
| 12 | 97 |
| 13 | 98 |
| 14 | 98 |
| 15 | 99 |

Conclusion

Two deployments per year would result in a 95% probability of obtaining a shuttle "snapshot" during magnetically quiet conditions in the five-year interval between chart epochs.

telemetry links, were also explored. It was concluded, however, that simply increasing the number of tracks recorded on the tape and packing the data offered the most reasonable solution to the expanded data requirements.

The Spartan carrier requires a given degree of attitude control to align its horizon scanners and sun sensors within a given window. The attitude of the Spartan carrier is presently maintained through the use of cold gas thrusters. Alternatives in extending the attitude control system include increasing the cold gas storage tanks; reducing the sensitivity of the thrusters, thereby reducing the required amount of gas to operate over a given period of time; magnetic torque bars; and spinning the spacecraft and momentum wheels. It was concluded that by increasing the cold gas storage tank minimally, fine tuning the individual pulses, and using less than full burst would significantly increase the efficiency of the cold gas system to cover the increase in the mission life. It should be noted that spinning the spacecraft would complicate the data reduction required, prohibit the use of solar panels, and vastly complicate the recovery of the vehicle by the Shuttle.

The Spartan carrier is presently powered by two LR 350 and one LR 40 silver zinc batteries that weigh approximately 360 pounds each. The obvious way to increase the power supply is to increase the batteries; however, weight limitations are critical. Lengthening the mission to seven days would require seven batteries, which increases the total battery weight to approximately 2400 pounds, exceeding the Spartan limit. Augmenting the battery power with solar arrays to provide charging on the daylight side, interspersed with 36 minutes of eclipsed darkness, would be the best alternative in augmenting the power for a seven-day mission.

The study on the required shielding and compensation of the Spartan carrier to reduce its influence on the magnetic sensors was, by necessity, theoretical in nature and establishes what is felt to be very conservative limits. Several things should be kept in mind when reading ORI Report No. 2356. First, the report deals with frequencies at 200 or less hertz. Traveling at 7.2 km per second, there should be no detectable signal from geological origins greater than a hertz. A prewhitening scheme for the data could be employed to considerably reduce the frequencies of concern. Second, when considering the magnetic fields produced by currents flowing through wires, it is unrealistic to suppose that the wires will appear to be infinitely long or twisted pairs or any of the geometric configurations considered in this report because the Spartan has a limited spatial domain and all loops must be closed. A real problem exists if the currents flow in closed loops that do not tend to cancel each other out. The easiest way to ascertain these effects is to perform actual calibration measurements on an existing Spartan. Spartan II is scheduled for magnetic calibration measurements in early spring 1985.

Table 3. Spartan system characteristics.

- Launch Date:
  Flexible (Quick Response Shuttle Payload)
- Mission Life: up to 40 hours
- Orbit: not critical
- Launch Vehicle: STS-KS/VAFB
- Remote Manipulator System: required
- Deployable Structure
  - Weight 1136 Kg
  - Length/Diameter: mission dependent
  - Attitude Control: 3-axis stabilized (CGT)
  - Power: self-contained
  - Thermal: active & passive control
  - Data Capture: onboard recorder (Bell & Howell Mars 1400 $5X10^8$ Bits)
- First Deployment August 1984
  Second Deployment Last Quarter Calendar 1985
  Third Deployment Fiscal 1986

The ORI report recommends that these measurements be used to determine the extent of separation required between the magnetometer and the Spartan. To study the problem of orbital determination, ORI subcontracted to OAO Corporation; this report is included as Appendix C. OAO has erroneously assumed that an orbital positioning capability of 50 m in any direction was required. As discussed in the previous section on accuracy requirements, an orbital determination within 500 m is seem to be adequate for world charting purposes. However, due to the inhomogeneity of the atmosphere in the resulting drag at these orbital altitudes, the task of tracking at either 500 m or 50 m is about equally difficult. OAO suggests that if GPS receivers are available for spacecraft in the late 1980s, if the power requirements to operate such receivers do not exceed the power budget of the Spartan magnetometer experiment, and if the weight consideration of the receiver does not exceed the weight limitations of the Spartan magnetometer experiment, then a Global Positioning System (GPS) onboard receiver would be the best alternative. Other alternatives examined were the NASA space flight tracking and data network in conjunction with a tracking and data relay satellite system and the Smithsonian Astrophysical Observatory's laser tracking system.

## Cost estimates and alternatives

Determining the cost associated with conducting geomagnetics surveys from Shuttle-deployed, space-borne platforms was both the most difficult and the most disappointing of all tasks. The present cost incurred by the Navy in conducting geomagnetic surveys to support DMA's world charting mission was first determined to place the cost figures for the space-borne surveys in perspective. In making any comparisons, however, it should be remembered that the quality of the data base produced by instantaneous global surveys is far superior to the quality of a data base produced by the present Project MAGNET aeromagnetic survey platform, which is restricted both spatially and temporally. An authoritative cost figure of operating Project MAGNET was obtained from CAPT J. M. Sears, Commanding Officer, U. S. Naval Oceanographic Office. His estimates are included as Appendix D. According to this appendix, the Navy currently expends a little over $4 million annually in conducting geomagnetic vector surveys. These estimates do not include data reduction cost. The amount of data to be reduced in both terms of samples/seconds and number of parameters is about equal for both the current aeromagnetic and the proposed space-borne magnetic surveys.

A rough order of magnitude cost estimate to modify the Spartan to perform geomagnetic surveys was produced at NASA/Goddard for their Geophysics Division. Based upon these estimates the Geophysics Division recommended using the Spartan carrier to conduct the space-borne geomagnetic surveys. A cost summary of this initial rough order of magnitude study is presented as Table 4. The study, however, was not explicit with regard to launch and transport cost. At the recommendation of the Geophysics Division, Jesse Moore, Assistant Associate Director of Space Flight, was asked to confirm the correctness of the rough order of magnitude cost study, and to elaborate on whether or not these included launch cost. His reply is included as Appendix E. His response significantly impacts the cost effectiveness of using the Shuttle to conduct global geomagnetic surveys.

The cost of manifesting cargo on the Shuttle is highly dependent upon whether the cargo is classified as a primary or a secondary cargo element. If a cargo is considered a primary manifest item, then it must be costed under the NASA/Air Force Memorandum of Agreement on reimbursement of launch and associated services for the use of the Space Shuttle. If, however, the Spartan could be considered a secondary or tertiary cargo element, then the possibility of a free flight exists. The significance of Jesse Moore's response is that he has identified the Spartan project as a probable primary cargo manifest element. As such, it is subject to the cost under the NASA/Air Force Memorandum of Agreement. The agreement states that the cost of a launch and supported services will be priced at $29.8 million in FY75 dollars and escalated based on the U. S. Department of Labor, Bureau of Statistics Bulletin titled *Productivity and Cost*, Table 1, compensation per hour column. Since this project is proposed to be an ongoing global survey, it is assumed to be a firm DoD commitment rather than a planned DoD commitment. Figure 7 illustrates how the charge factor for manifesting is determined. The Spartan and the Spartan flight support structure span the width of the cargo bay and take up a payload length of approximately 6 ft. The weight of a Spartan depends on the mission for which it is configured, but it is reasonably limited to between 2000 and 4000 pounds. Thus, regardless of whether one uses the payload weight or the payload length to determine the load factor, the load factor of a polar orbit launch is approximately one-tenth. A load factor of one-tenth plus a firm commitment will assure that Spartan must be categorized as a primary cargo element. Using the escalator factor from the NASA near-term billing forecast and a

Table 4. Spartan/magnetometer summary.

| | | Weight | Size | Power | Data Rate | Cost |
|---|---|---|---|---|---|---|
| Basic Spartan 2 | | 900 kg | 1.09x1.30x1.32 m | 250–400 W | Housekeeping <0.1 kbs | 2.0 M |
| Magnetometer | Sensor | 0.6 kg | 11.4x5.72x5.8 cm | 2.0 W | 2–3 kbs | $0 |
| | Electronics | 2.6 kg | 22.2x17.8x11.4 cm | | | |
| Boom (Astromast) | | 6–8 kg | 0.46x0.3x0.3 m | 10–20 W (movement only) | — | $0.5–2.0 M |
| Extra Batteries (2 LR350 Ag-Zn) | | 360 kg | 0.43x0.6x0.6 m | supply 30,000 W-hr | — | $40–50 K |
| GPS Receiver | | 20–30 kg | 0.4x0.3x0.2 m | 43 w | 0.064 kbs* | $0.05–1.4 M |
| Redesign Electronics | | | | minus ? w | | $50 K ? |
| Launch | | | | | | Unavailable $4 M ? |
| Project Support | | | | | | Unavailable |
| Refurbishing Each Launch | | | | | | $50 K ? |
| Initial Total | | 1301.2 kg | | 295–445 W+ | 2–3.164 kbs | $2.64–5.23 M |
| Total per launch (20 Flights) | | | | | | $0.2–03 M |

*32 bit digital registers read every 0.5 seconds
+ 60,000 W-hr from 4 batteries will last 135–203 hours

base of $29.8 million FY75 dollars, the Shuttle launch cost in 1988 is computed to be $78.1 million. Using a load factor of one-tenth, the charge factor computed from Figure 7 predicts a 1988 Spartan launch cost of approximately $10.4 million.

The cost estimate of $10.4 million per launch is in good agreement with that provided by NASA's Johnson Space Center. The NASA/Johnson cost estimates, included as Appendix F, were provided in response to the original inquiry that Jesse Moore forwarded to them. This estimate included the additional cost of payload-related optional services. These additional services increase the cost per launch by approximately $2 million. The requirement of conducting two surveys per year, then, places the annual cost at a little above $24.8 million or the cost between chart publication epochs every five years at $124 million. Whether or not the increase in the data base quality justifies the increase in data collection must ultimately be a user judgment. However, in view of the high cost of conducting Shuttleborne geomagnetic surveys from a free-flyer such as the Spartan, careful attention should be given to other options.

This study focused on a retrievable sensor probe. The system required to support retrievability consist of a yoke device to secure the satellite while in the shuttle bay, the use of the remote manipulator arm for deployment and retrieval, and a grappling catch on the satellite. The yoke accounts for about half of the total launch weight and the majority of the shuttle bay space used by the Spartan System. These factors combined with the required use of the remote manipulator arm drive the cost (of deployment) beyond that of the instrument suite itself. In a follow on study (reported separately) the concept of an expendable probe not requiring such high deployment cost is examined.

Space-borne global geomagnetic surveys serve other interests in addition to chart production. The magnetic field is the dominant physical dynamic force in a region from roughly the ionosphere to the magnetosheath, and an understanding of it is essential to understanding the physics of the magnetosphere and also the dynamics of the earth's crust, core, and mantle. As such, the need for an improved and current geomagnetic data base is recognized by many investigators in separate fields. The concern over an improved data base has spawned two ad hoc committees and one official proposal by the group at NASA Headquarters. One committee, chaired by Dr. Jim Heirtzler of Woods Hole Oceanographic Institution, examined possible means of conducting spaceborne surveys during the solar minimum between MAGSAT and the Geopotential

## DETERMINATION OF CHARGE FACTOR (Cf) FOR 160 NMI

$$\text{PRICE} = C_f \times \text{DEDICATED PRICE}$$

$$\text{LOAD FACTOR} = \left\{ \begin{array}{c} \dfrac{\text{PAYLOAD WEIGHT, LBS}}{\text{SHUTTLE CAPABILITY}} \\[2ex] \dfrac{\text{PAYLOAD LENGTH, FT}}{60} \end{array} \right\} \text{WHICHEVER IS GREATER}$$

| SHUTTLE CAPABILITY | |
|---|---|
| INCLINATION IN DEGREES | WEIGHT IN THOUSANDS OF POUNDS |
| 28.5 | 65 |
| 56 | 57 |
| 90 | 37 |
| 104 | 30 |

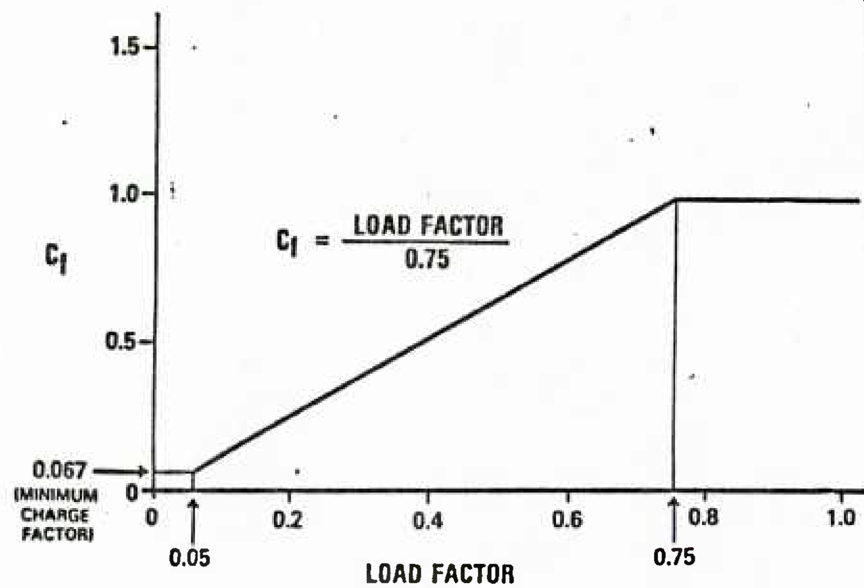


*Figure 7. Determination of charge factor (Cf) for 160 nmi.*

Research Mission, which could fly as early as 1992 but is currently unfunded. The other ad hoc committee, the International Working Group on Satellite Geomagnetic Surveys, is now preparing a white paper that would carry the endorsement of the International Association of Geomagnetism and Aeronomy. Dr. Tom Fischetti of the Geodynamics Group at NASA Headquarters has proposed that a MAGSAT follow-on mission be flown under the auspices of the NASA Explorer program. Accordingly, NASA contracted Johns Hopkins University, Applied Physics Laboratory, to do a rough order-of-magnitude cost study of such a mission. The mission would have a planned longevity of 30–60 months of continuous data collection. The rough order-of-magnitude cost estimates were $60 million. An additional $20 million would be required to cover NASA's expenditures in this project. In addition to these monies, which now total approximately $60 million, would be the cost of a launched vehicle. The Scout rocket is one possible launched vehicle and would result in a 30+ month mission. At the moment no surplus Scouts are available to NASA. The estimated cost of producing a new Scout lies somewhere between $6 and $7 million, depending upon what options are required. While using the Shuttle as a launch platform is very much more expensive, it results in a greater longevity of approximately 60 months.

There is an international interest in geomagnetic surveys. The British Geological Survey works in conjunction with the Naval Oceanographic Office to produce a model from which the world charts published both in the United States and in the United Kingdom are constructed. They also are prime users of any data generated for charting purposes. The British were asked to consider supporting any endeavor to produce global geomagnetic data base. While their response stops short of offering financial assistance to undertake such an endeavor, they did indicate the possibility of being responsible for producing certain components to be used in the satellite. As an example, the solar panel modification to the present Spartan could be supplied by the United Kingdom. NASA has undertaken a joint study with Canada of the characteristics of long-lived optical pump scalar magnetometers for use in space. It is possible that Canada could supply such an apparatus for a space-borne mission. While neither of these

items constitute the majority of cost factors in such a survey, they are critical and do serve to illustrate the degree of interest in such surveys in the international arena.

If no further global geomagnetic surveys are implemented in the next decade, then optimizing current resources to successfully update the MAGSAT data base becomes crucial. Barker and Barraclough (1985) have illustrated the effects of nonuniform distribution of observatory data upon the modeling of secular variation and have examined the possibility of optimizing the modeling process through the prudent use of Project MAGNET's aeromagnetic surveys. Last, when considering alternatives, it should be noted that the Air Force Geophysical Laboratory (AFGL) is currently collecting spaceborne geomagnetic vector data. These observations are made as part of the Defense Meteorological Satellite Program (DMSP) and are intended to aid in studying field-aligned currents and other physical phenomena governing the magnetosphere. Such a mission does not require continuous and calibrated measurements of the earth's magnetic field, which are essential to a world charting mission. The magnetometer is located near the power supply of the satellite and is heavily contaminated by the platform's environment. Further, the sensors employed are fluxgate vector instruments. These instruments will experience a drift with time. On MAGSAT and the proposed Spartan mission and on all proposed field charting missions, a scalar absolute instrument is run concurrently with the fluxgate vector instrument to calibrate this drift. While the measurements made aboard the defense meteorological satellite are not readily usable in producing global models and world charts, the possibility exists that they might be used for these objectives. Investigating the suitability of these measurements to the charting function would constitute a separate research effort.

## Research requirements

Given the probable launch cost of $10.4 million per Spartan deployment, reducing the number of deployments per chart epoch period will obviously result in substantial savings. However, the fewer deployments initiated, the less likely one is to collect data during magnetically quiet times. The plan now calls for 10 deployments every five years at a total cost of $124 million. At what point do successive deployments become redundant to the world charting mission? Can ground-based observatory data be used to correct the satellite data? If so, how much ground data is required?

These and similar questions are largely unanswered which, to some extent, is due to the great redundancy of MAGSAT data. The continuous collection of data over a six-month period has generated enough data so that investigators could, and did, choose data taken during the magnetically quietest of times. No systematic study has been made of the data collected during more magnetically active times. Clearly, a reanalysis of MAGSAT data during different levels of magnetic activity is required to answer the question of how much data is sufficient. Data collected during magnetically active periods need corrections; since they need correcting, can it be done with observatory data? It may well be that the magnetic activity or noise is both random and zero biased with respect to the modeling parameters; if so, then the least-squared residual values will vary as a function of the magnetic activity, but the model parameters will be stable. If, on the other hand, the parameters vary with magnetic activity, then a comparison with ground-based data may well lead to a correction model.

A second line of research that promises great savings is an investigation of AFGL's DMSP data. This data source is currently being collected and is readily available. The two limiting factors (as mentioned in the previous section) are the severe platform contamination and the instrument drift. A research effort aimed at recognizing and analytically minimizing the platform contaminations and correcting long-term instrument drift by comparing observations along a quiet baseline with observatory prediction is required. Satellite mechanics ensure the existence of a quasi-baseline, and the density of observations in Europe allow a modeling of secular change at DMSP altitudes above Europe. The possibility exists that current DMSP surveys may fulfill charting needs, but the continuation of magnetic data collected from future DMSP is not assured. However, if it can be shown that such data is sufficient for the world charting mission, then the inclusion of magnetic sensors on future DMSP missions would be fully justified.

Last, if satellite geomagnetic data is not available in the future, then maximizing current resources become crucial. Barker and Barraclough (1985) have taken the initial steps in such research and have shown how Project MAGNET's present aeromagnetic survey effort could be used to best complement current magnetic observatory operations in obtaining secular variation models. The precise frequency and location of the aeromagnetic surveys have yet to be worked out.

In conclusion, regardless of what future direction surveys to support the world charting mission take, the research efforts described above promise substantial long-term savings.

# Appendix A: Spartan/Magnetometer Experiment Operating Lifetime Analysis. ORI, Inc. TR 2354

ORI
Silver Spring, Maryland 20910

# SPARTAN/MAGNETOMETER EXPERIMENT OPERATING LIFETIME ANALYSIS

TASK 07C UNDER NASA CONTRACT NAS5-28057
(ORI DESIGNATOR GSFC ASP 07)

30 AUGUST 1984

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# 1.0 ABSTRACT

This study was undertaken at the request of the National Aeronautics and Space Administration through Goddard Space Flight Center to explore the possibility of and problems in extending the lifetime of the Spartan magnetometer missions from 40 hours to seven days (168 hours). Extending the lifetime requires changes in three main areas: data recording, attitude control, and power. Alternatives and extensions are considered for each area and the most feasible solution is recommended.

With close scrutiny of the data requirements, data compression, and the addition of a 28-track head, the present MARS 1400 tape recorder will be sufficient for data recording over seven days. With the addition of more gas and thruster improvements, the present attitude control system will be adequate for moderate pointing requirements with exact position data determined after the mission. Finally, to meet the proposed power load requirements, solar arrays will be required at a cost of about $400,000. The two arrays are each 1.6m$^2$ and will easily fit aboard the Shuttle. Additional batteries, rather than solar panels, would be adequate for a mission of up to about 5 days if no other weight is added to the present system.

# 2.0 ALTERNATIVES

## 2.1 DATA RECORDING

The presently planned data recording mechanism for Spartan 2 and 3 is a modified Bell and Howell MARS 1400 LTB tape recorder with a 14-track head and a total capacity of $10^{10}$ bits. Two tracks are used for clocking, leaving either 12 tracks for data with no redundancy or 6 tracks with redundancy. Each pass can be up to 16 hours long, allowing up to 96 or 192 hours of recording.

Assuming 2-3 kilobits-per-second (kbs) of data from the magnetometer instrument over seven days, the data storage required is $(3000)(60)(60)(24)(7) = 1.8 \times 10^9$ bits leaving $8.2 \times 10^9$ bits with a 14-track head and $18.2 \times 10^9$ bits with a 28-track head. Areas for improvement include buffer storage, especially for housekeeping data; reduction of sampling rate, duty cycle, precision and information redundancy; and other data compression and encoding techniques. Twenty-eight and 42-track heads are available for the MARS tape recorder; the 28-track head doubles the capacity and the 42-track head increases capacity further but with a decrease in bandwidth.

Other options considered were bubble memory devices, optical disk storage, and telemetry links. Space-qualified bubble memory and optical storage are not yet available and are limited by power requirements, costs and space radiation effects. In addition, bubble memory devices use fairly strong permanent magnets and electro-magnets and would hamper magnetometer precision. A telemetry link would greatly affect the design and power requirements of the Spartan, require data storage or transponder equipment on the Shuttle, complicate the mission and also affect the magnetometer performance with interference from the antenna.

## 2.2 ATTITUDE CONTROL

Presently, two to four tanks of pressurized gas are planned for cold gas attitude control for short Spartan missions. The amount of gas required is highly dependent on mission length and pointing accuracy requirements. A seven day mission with high pointing accuracy requirements might require twelve bottles of gas with their attendant weight and space requirements and additional danger of explosion.

Alternatives or additions to a cold gas system include magnetic torquer bars, spinning the spacecraft, and momentum wheels. Magnetic torquers are power consumers and would produce too much interference to the magnetometer. Spinning the spacecraft prohibits extended solar panels, complicates magnetometer measurements and complicates spacecraft pointing with little attendant decrease in gas requirements. Momentum wheels are costly ($120 - $150K) and require magnetic torquers or a gas system with almost the same amount of gas for unloading the wheels. Most disturbances to the spacecraft attitude are additive; only cyclical effects such as gravity wells can be absorbed and then released over the orbital period with zero momentum build-up.

Fine tuning the individual impulses and using less than full bursts will significantly increase the efficiency of the cold-gas system. Balancing the spacecraft aerodynamically and reducing the pointing accuracy

requirements, particularly for yaw, will also hold down the amount of gas required. The Spartan project office is currently exploring the use of pulse-width modulation for smaller pulses rather than the present pulse frequency method.

## 2.3 POWER

### 2.3.1 Power Alternatives

The present Spartan design calls for two LR350 and one LR40 (only for back-up recovery operations) Silver-Zinc batteries. Each LR350 battery weighs about 180 kg and produces up to 550 Amp-hours (A-hr) at 28 Volts nominal, yielding 15,400 Watt-hours (W-hr).

Figure 2.1 and Table 2.1 compare the principal types of storage batteries used on space projects. Not shown are nuclear batteries which have a low specific energy, high cost and low proven reliability.

Lithium batteries are also unproven and costly and require high temperatures. Nickel-cadmium batteries have a permanent magnetic field at 30 cm of 300-900 gammas, whereas silver-zinc and silver-cadmium batteries have a field of less than 1 gamma. Fuel cells require extensive thermal control and cryogenic tanks but may offer an alternative if Shuttle problems of filling, monitoring, and venting could be overcome. Goddard has little experience with them, though, as they have been used only on manned missions.

Another alternative is using flywheels to store power as well as provide momentum and attitude control. Disadvantages include size, weight, cost, and a requirement for cold gas or magnetic torquer momentum unloading system (unless momentum could be stored and released through the Remote Manipulator Arm to the Shuttle), and lastly, lack of availability and proven performance (even though the technology is developed).

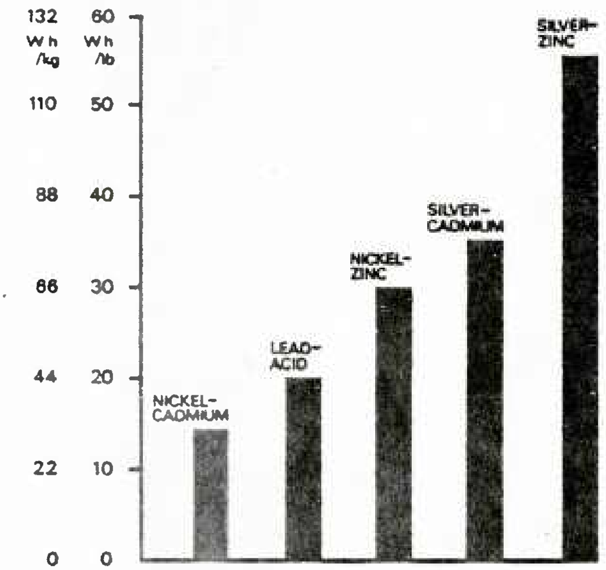


**Figure 1.1 Comparison of energy per unit weight output for rechargeable battery systems**

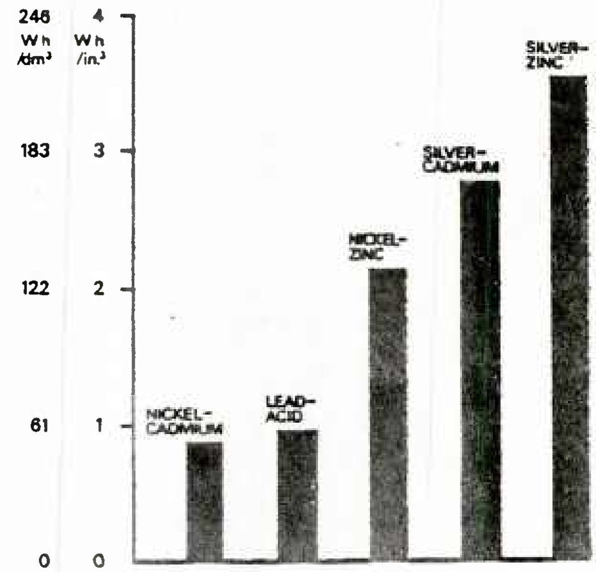


**Figure 1.2 Comparison of energy per unit volume output for rechargeable battery systems**

FIGURE 2.1. COMPARISON OF STORAGE BATTERIES
(From page 4 of Crompton, T.R., Small Batteries: Volume 1, 1982)

TABLE 2.1
COMPARISON OF STORAGE BATTERIES

| | Nickel-Cadmium | Silver-Cadmium | Silver-Zinc | Lithium | Fuel Cell |
|---|---|---|---|---|---|
| Volts per cell | 1.2 | 1.4 | 1.5 | 3.0 | 0.9-1.1 |
| Typical number of cells | 20-28 | | 18-24 | | 32 |
| Capacity (Amp-hours) | 1-100 | 1-300 | 5-2000 | | |
| Power (Watts) | 30-100 | | | | 2-12,000 |
| Power density (W/kg) | | | | | 100-200 |
| Specific energy (W-h/kg) | 30-39 | 32-110 | 88-220 | 200-300 | |
| Density (x $10^{-15}$ Wh/m$^2$) | 61-91 | 110-153 | 183-488 | | |
| Cycle life (25% DOD, 5$^o$C) | 40000 | 3000 | 400 | | 2500 hrs |

Table 2.2 compares several types of solar arrays and Figure 2.2 shows a possible solar array configuration. Price and flight experience factors point towards the use of silicon arrays which typically cost $1,000 per Watt for space quality. Exact sizes and costs depend on the Shuttle's orbit, eclipse time, orbit temperature, and magnetic requirements.

Lastly, the Spartan could be brought on-board the shuttle half way through the mission and be recharged. This would involve extra shuttle costs and astronaut time.

### 2.3.2 Power Requirements

The estimated power requirements are 150 Watts for attitude control, 150 Watts for data storage, 25 - 125 Watts for thermal control, and 2 - 5 Watts for the magnetometer for a total power load of 327 - 430 Watts. These numbers are very conservative and shold be revised after the first flights. In addition, use of less power-consumptive components, such as CMOS chips, would decrease the power load.

The final energy in the battery is:

$$E_f = E_{in} - E_{out} + E_o \text{ or } E_f = 0 = P_{into}\, T_d\, m\, \beta_B\, \beta_D\, \beta_C - P_L\, T_n\, m + E_o\, \beta_D\, \beta_B$$

and the power required from the solar array is:

$$P_{SA} = P_L + P_{into} \text{ which implies } P_{SA} = P_L + \frac{P_L\, T_n\, m - E_o\, \beta_D\, \beta_B}{T_d\, m\, \beta_B\, \beta_C\, \beta_D}$$

where:

$E_f$ = final battery energy

$E_{in}$ = energy into the battery

$E_{out}$ = energy out of the battery

$E_o$ = initial battery energy = 30,800 W-hr presently

$P_{into}$ = power from the solar array to the battery

$P_{SA}$ = power out of the solar array after conversion inefficiencies

$P_L$ = power load of the spacecraft = 350-400 Watts

$T_d$ = sunlight (day) time = $90-T_n$ = 50-54 minutes for low inclination orbit

$T_n$ = eclipse (night) time = 36-40 minutes for low inclination orbit

m = number of orbits = 27 (40 hours), 112 (7 days), 160 (10 days)

$\beta_B$ = battery charge-holding efficiency = 0.75

$\beta_D$ = discharge regulator efficiency = 0.8

$\beta_C$ = charger electronics efficiency = 0.8

The following cases apply the formula above at the extremes:

Case 1: Assume no solar array with only two Silver-Zinc batteries (the present plan); then the length of the mission is $E_o \, \beta_D \, \beta_B \, / \, P_L$ or 47 hours for a 400 Watt load. Lengthening the mission to seven days would require seven batteries, each weighing 177 kilograms, for a total of 1,239 kilograms -- exceeding the Shuttle limit. Approximately 500 kilograms is allotted for the instrument; this would allow five batteries yielding 117 hours of power.

Case 2: Assume an indefinite mission with no initial battery charge ($E_o = 0$), then $P_{SA} = P_L + P_L \, T_n \, / \, T_d \, \beta_B \, \beta_C \, \beta_D$ or 1,067 Watts for a 400 Watt load. This array would cost on the order of one million dollars.

Case 3: Assume a seven day mission and a solar array providing some charge to the batteries, then $P_{SA}$ = 351 Watts for a 400 Watt load and 36 minute eclipse. This is the best alternative for a seven day mission. The arrays would cost \$350 - \$400 thousand.

Case 4: Assume that the batteries cannot be charged feasibly in-orbit and are used only at night with the solar arrays carrying the load when sunlit ($P_{SA}$ = 400 Watts), then $m = E_o \, \beta_B \, \beta_D \, / \, P_L \, T_n$ or 77 cycles which is 115 hours for a 400 Watt load and 36 minute eclipse.

TABLE 2.2
COMPARISON OF SOLAR PANELS

| | Silicon | Gallium-Arsenide | Flexible |
|---|---|---|---|
| Efficiency | 15% | 18% | |
| Specific Power (W/kg) | 25 | 100 | 44-200 |
| Power Density (W/m$^2$) | 125 | 200 | |
| Cost (per Watt) | $500-1500 | $3000-5000 | unproven |

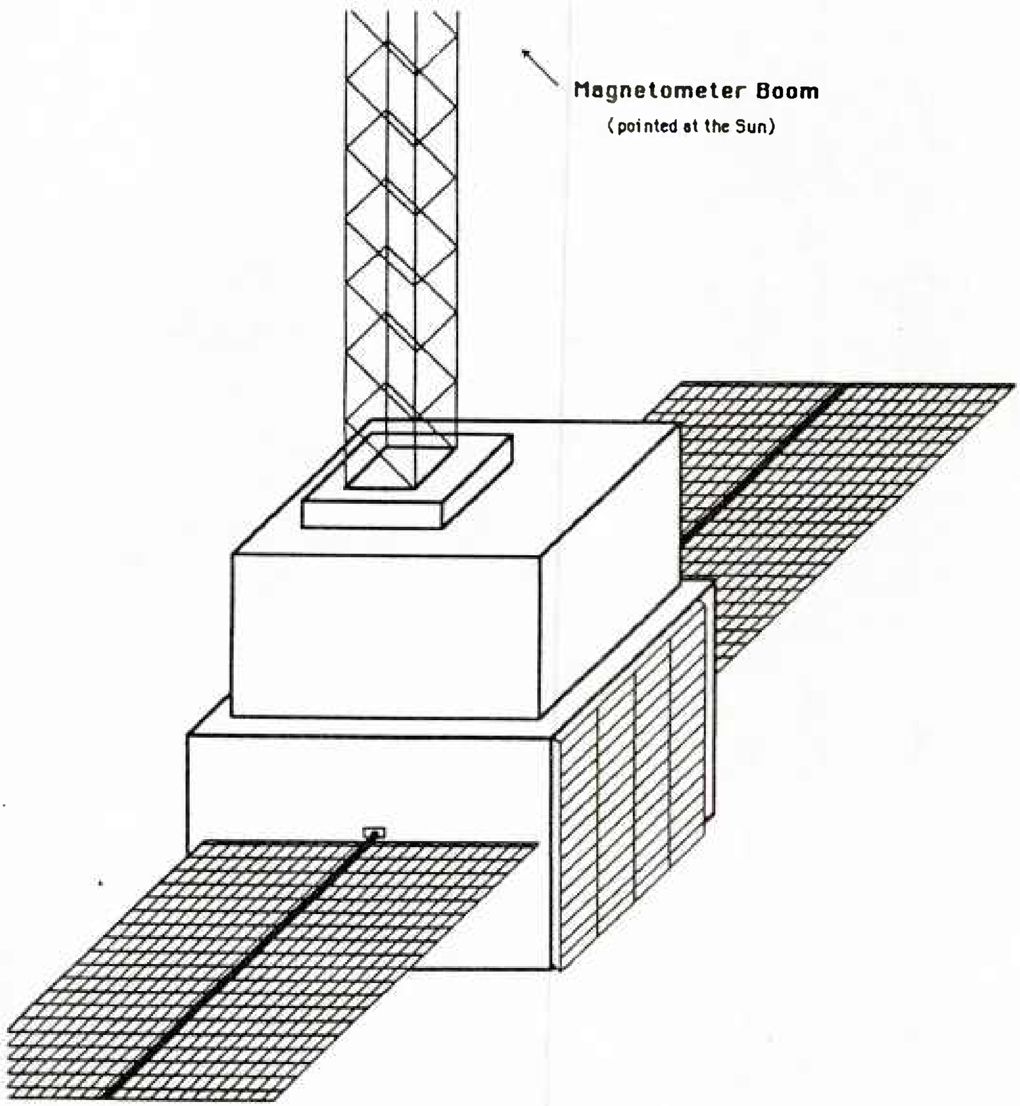


FIGURE 2.2. POSSIBLE SOLAR ARRAY CONFIGURATION

# 3.0 CONCLUSIONS

The numbers available only order-of-magnitude estimates as every factor is dependent on the others. Minor modifications to the data collection and attitude control systems should be sufficient for a seven day mission. However, the cost driver is power. Spartan could hold enough batteries for 4-5 days if the power load is decreased; otherwise, solar arrays are required with a cost of about $400,000. These estimates should be refined as requirements are clarified.

# 4.0 ACKNOWLEDGMENTS

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# Appendix B: Spartan/Magnetometer Experiment EMI/EMC Analysis. ORI, Inc. TR 2356

TECHNICAL REPORT 2356

ORI
Silver Spring, Maryland 20910

# SPARTAN/MAGNETOMETER EXPERIMENT
# EMI/EMC ANALYSIS

TASK 07B UNDER NAS5-28057
(ORI DESIGNATOR GSFC ASP 7)

4 SEPTEMBER 1985

PRODUCED FOR:
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## SECTION 1
## INTRODUCTION

### BACKGROUND

The Spartan program is designed to provide short-duration free-flight opportunities for a variety of scientific studies. The Spartan platform consists of an Attitude Control System (ACS), a data-handling system, and a power system. The ACS provides pointing and stabilization for Spartan experiments. The data-handling system provides data conditioning/sampling and records all mission data on a tape recorder. The power system provides the basic power and electrical distribution for the Spartan and the experiment payload. These Spartan system components are based on equipment and procedures developed and used successfully during the sounding rocket program.

A future Spartan experiment will be to study the sources of the observed magnetic field which are identified with the earth. The experiment payload includes a magnetometer. The requirements placed on Spartan differ from those of the first Spartan flights since the magnetometer will be highly susceptible to components of Spartan's electromagnetic environment. The major point of concern is the magnetic field generated by low frequency (below 200 Hz) currents within the Spartan platform. The magnetometer sensitivity is 1 nanotesla (nT); therefore, there is a requirement that the maximum magnetic field strength generated by the Spartan components at the magnetometer be limited to 0.5 nT or less.

## OBJECTIVE

The objective of this report is to identify the electromagnetic sources within the Spartan platform and suggest methods to eliminate or suppress these electromagnetic sources.

## APPROACH

An in depth effort to model the magnetic environment generated by Spartan was not possible due to the extreme magnitude of such an effort, the time limitations, and the lack of completed design information pertaining to Spartan.

The approach taken in this analysis was to identify sources of magnetic fields within Spartan and to estimate typical and worst case magnetic field strengths produced by these Spartan components. Where possible manufacturer's data was used for these estimations. Also, measurement data from the previous sounding rocket program was utilized for these estimations. The sounding rocket program was the forerunner to Spartan and most of the components (ACS, solenoid valves, gyros, and data-handling system) which comprise Spartan are similar to that of the sounding rocket program. Finally, methods to eliminate or suppress these sources of magnetic fields are presented.

SECTION 2
SPARTAN SYSTEM DESCRIPTION

## GENERAL

Spartans are built from milled aluminum plates that are bolted together. No welding is used. The structure contains the Spartan's support systems: the ACS, the data-handling system, and the power system. This arrangement provides a service module (Figure 1) to which the experiments, associated experiment systems, and any additionally required structural supports are mounted.

## ACS DESCRIPTION

The ACS, which provides pointing and stabilization for Spartan experiments, consists of two main assemblies: the Attitude Control Pneumatics (ACP) and the Attitude Control Electronics (ACE). The ACE processes signals from the various attitude sensors and produces thruster commands to the ACP.

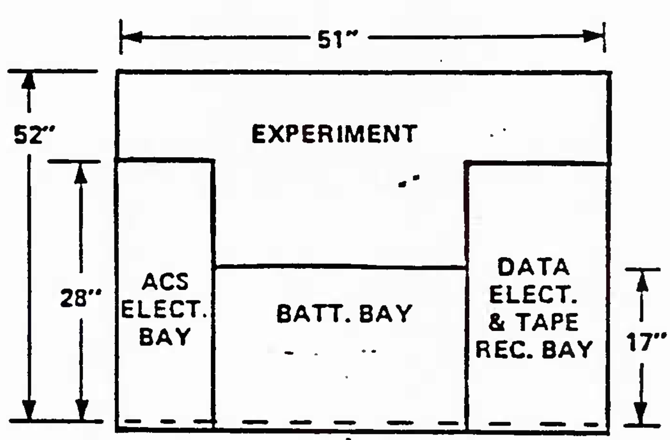


Figure 1. Spartan 2 Module Locations.

The ACP consists of a variety of sensors used to determine the attitude of the Spartan. Three sensors are used: tuned rotor inertial gyros, solar sensors, and a star tracker. The tuned rotor inertial gyros are tuned restraint displacement type gyros that are similar to NASA standard gyros that are used to indicate the angular displacement of the body from some initial attitude. Various types of analog solar sensors are used to acquire and point two axes of the Spartan at the Sun. Those currently in use are taken from SPARCS sounding rocket application: coarse solar cells, Miniature Acquisition Sun Sensor (MASS), Lockheed Intermediate Sun Sensor (LISS), and Fine Sun Sensor (FSS). The star tracker used by the Spartan is the type that has been used in the sounding rocket program. The pneumatics system consists of solenoid valves, regulators, and other components used in the sounding rocket program. All components are mounted on a single pneumatics plate.

The ACE is mounted on a single cold plate and consists of the following units:

1. Valve control Unit (VCU) processes the error signals to command the ACP solenoid valves "ON" thus correcting pointing error.

2. Attitude Control Power Converter (ACPC) operates off the 28-Volt (nominal) DC bus provided by the battery power subsystem. The ACPC supplies regulated AC and DC voltages necessary for operating all ACS electronic units and sensors including the gyros and star tracker.

3. Stellar Tracking and Rocket Attitude Positioning (STRAP V) unit contains circuitry that compensates and closes the analog torquer loop about each gyro axis, as well as gyro drift compensation and rate integration circuits. The digital electronics for controlling the rate of the system maneuvers are also contained within the STRAP unit. These electronics have been used in a similar manner in the sounding rocket program.

4. Sensor Interface Box (SIB) processes the analog signals from the various attitude sensors and uses digital commands from the computer to set gains and logic configurations for various desired control algorithms and system operational logic details.

5. Attitude Control Programmer acts as a long-period timer for the computer. The numerous outputs are programmable to change state after preset time intervals have elapsed. This component has previously been used in the sounding rocket program.

6. Attitude Control Computer (ACC) provides the required logic functions in addition to the previously mentioned pointing system program storage.

## DATA-HANDLING SYSTEM

The two main groups of data-handling components are: data conditioning/sampling modules which perform Pulse-Code Modulation (PCM) encoding of all payload data, and a unit consisting of a tape recorder, a tape

controller unit, and a Time-Code Generator (TCG). Data are nominally encoded at a rate of 12.5 kbps. The tape recorder records all payload data throughout the mission phases. The recorder, a Bell and Howell Mars 1414, is a multitrack, multispeed machine that can record data either by direct analog or by Frequency Modulation (FM). All data are formatted and handled by the data-handling system. This system has previously been used in the sounding rocket program.

## POWER SYSTEM

The power system provides the basic power, electrical distribution, and control of the Spartan flight systems. Batteries provide all of the electrical power required for the Spartan mission. Two batteries are used as the primary power source and a third battery provides a reserve power source to ensure available power for the recovery sequence. Each battery is packaged in an individual battery box and consists of silver zinc cells and a thermal battery monitor. All batteries are connected to the main power bus through power isolation diodes. Thermal control is provided by thermal louvers on two sides of the Spartan. The thermal louvers slide to expose or cover the radiator surfaces. The thermal louvers are passive devices that open and close based on a preselected temperature range.

SECTION 3

ANALYSIS

## GENERAL

This section provides a quick-look analysis of the major magnetic sources contained onboard the Spartan. First a list of the major magnetic sources onboard the Spartan is presented. Next, an estimate of the magnetic field strength of each magnetic source is calculated. Finally, methods to eliminate or suppress these magnetic sources are presented. The requirement is that the magnetic field generated by Spartan be maintained at 0.5 nT or less at the magnetometer.

## SPARTAN MAGNETIC SOURCES

A review of the available Spartan documentation revealed the following Spartan components as major magnetic sources.

1. Batteries
2. Tape Recorder
3. Data Control Electronics
4. ACS
5. Wiring

## BATTERIES

Batteries provide all of the electrical power required for the Spartan mission. Two batteries are used as the primary source and a third battery provides a reserve power source to ensure available power for the recovery sequence. Each battery is packaged in an individual battery box and consists of silver zinc cells. Figure 1 indicates that the batteries are located in the center region of the Spartan module.

Manufacturer's data indicates that the magnetic field strength at a distance of 30 cm away from the battery is less than 1 nT. The battery bay height is approximately 43 cm. The overall height of Spartan is approximately 71 cm which leaves a distance of 28 cm from the top of the battery bay to the top of Spartan. Therefore, as long as the magnetometer is located above the overall top of Spartan, the batteries will not affect the magnetometer.

## TAPE RECORDER

The tape recorder records all payload data throughout the mission phases. The recorder, a Bell and Howell 1414, is a mulitrack, multispeed machine that can record data either by direct analog or by FM. The tape recorder has been modified by NASA personnel to meet the required installation and operational requirements for use on Spartan. The modification included additional electronics that were housed within the existing tape recorder housing.

Detailed information about the tape recorder and the modifications were not available.

In order to estimate the magnetic field strength of the tape recorder, an assumption was made that the tape recorder electronics generate negligible magnetic fields so as not to interfere with the tape recording and reproducing operations. Therefore, the tape recorder recording or reproducing magnet was assumed to be the major concern.

A typical recording or reproducing magnet is called a head, and it consists of soft iron pole pieces wound with coils of wire. During recording the head is biased with an alternating current in the 60 - 100 KHz range. The typical magnetic field strength of a tape recorder head is 0.65 to 0.82 T. Some method to suppress or eliminate this magnetic source is required.

## DATA CONTROL ELECTRONICS AND ACS

The data control electronics consists of data conditioning/sampling modules which perform PCM encoding of all payload data. The ACS, which provides pointing and stabilization for Spartan experiments, consists of the ACP and the ACE. The ACE processes signals from the various attitude sensors and produces thruster commands to the ACP. The ACP consists of tuned rotor inertial gyros, solar sensors, and a star tracker to determine the attitude of the Spartan. The ACE is mounted on a single cold plate and consists of

solenoid valve control units, power converter circuitry, interface circuitry, and a computer.

These electronic modules were used previously during the sounding rocket program. During the sounding rocket program, magnetic measurements were made in the laboratory. These magnetic measurements were performed with the sounding rocket systems operational. Magnetic data was collected from the sounding rocket program which includes the ACS (thrusters, gyros, and solenoid valves) and the data handling PCM hardware. Therefore, this data is representative of the magnetic field produced by these electronic modules contained within Spartan. The data indicates magnetic dipole moments of 91.97 $kT/m^3$ in the X direction, 68.23 $kT/m^3$ in the Y direction, and 54.15 $kT/m^3$ in the Z direction. The data also indicates the largest magnitude of the magnetic field in each direction to be 289.8 nT in the X direction, 476.8 nT in the Y direction, and 202.6 nT in the Z direction. The magnetic fields of these modules require elimination or suppression to meet the magnetometer sensitivity requirement.

## WIRING

Many wiring configurations will result from the interconnections required to interconnect Spartan and the equipment modules and to supply power to the various modules. The following is an analysis of three different commonly encountered wiring configurations.

Single Wire

A single current carrying wire produces a magnetic field and is calculated by:

$$B = \frac{\mu_0 I}{2 \pi r} \tag{1}$$

where, B = magnetic field strength, Tesla (T)

$\mu_0$ = permeability of free space = $4\pi \times 10^{-7}$ Wb/Am

I = the current in the wire, Amperes (A)

r = distance from the wire, meters (m)

By rearranging equation 1 into the following form:

$$r = \frac{\mu_0 I}{2 \pi B}$$

the distance separation required between the magnetometer and any single current carrying wire can be calculated. Table 1 indicates the distance separation required between the magnetometer and any single current carrying wire for various values of current to meet the 0.5 nT requirement at the magnetometer. The maximum current supplied by Spartan is 10 A which represents the worst-case for this configuration. Table 1 indicates a distance separation of 4 Km is required for a current of 10 A.

TABLE 1

Required Distance Separation for a Single Wire

| Current $I$ (Amperes) | Distance $r$ (meters) |
|---|---|
| 0.2 | 80 |
| 0.5 | 200 |
| 1.0 | 400 |
| 2.0 | 800 |
| 5.0 | 2000 |
| 10.0 | 4000 |

Two Perpendicular Wires

Two perpendicular current carrying wires produce a magnetic field which is calculated by:

$$B = \sin D \, (B_x^2 + B_y^2)^{1/2} \qquad (2)$$

where, $B$ = magnetic field strength, T

$D$ = angle between $B_x$ and point of interest, degrees

$B_x$ = magnetic field strength of one wire, T

$B_y$= magnetic field strength of the other wire, T

$B_x$and $B_y$in equation 2 are calculated using equation 1. Assuming the current in each wire to be equal and choosing the point of interest to be at a 45 degree angle from $B_x$, rearranging equation 2 (after substituting equation 1 for $B_x$and $B_y$) into the following form:

$$r = \frac{\mu_0 \; I}{2 \pi \left( \frac{B^2}{2 \sin^2 D} \right)^{1/2}} \tag{3}$$

the distance separation required between the magnetometer and the two perpendicular current carrying wires can be calculated. Table 2 shows the resulting distance separation requirements for various values of current to meet the 0.5 nT requirement at the magnetometer for this configuration. The maximum current of 10 A is the worst-case for this configuration and Table 2 indicates a distance separation of 4 Km is required.

TABLE 2

Required Distance Separation for Two Perpendicular Wires

| Current $I$ (Amperes) | Distance $r$ (meters) |
|---|---|
| 0.2 | 80 |
| 0.5 | 200 |
| 1.0 | 400 |
| 2.0 | 800 |
| 5.0 | 2000 |
| 10.0 | 4000 |

## Two Parallel Wires

Two parallel current carrying wires having the same direction of current flow produce a magnetic field which is dependent upon the point of interest. The magnetic field produced by each wire is calculated by equation 1. For a point of interest which lies in the same plane as the two wires, the direction of the two magnetic fields are opposite to each other at any point between the two wires. Therefore, the magnetic field in this region is equal to the difference of the individual magnetic fields and has the direction of the stronger magnetic field. As an example, for two wires spaced 5 cm apart

and a current in each wire of 10 A (maximum current available from Spartan), the magnetic field strength at a point 1 cm from one of the wires is 1.5 x $10^{-4}$T. A special case of this example is when the point of interest is of equal distance from both wires. This special case yields a magnetic field strength of zero because the individual magnetic fields are equal in magnitude but opposite in direction and the magnetic fields cancel each other.

For a point of interest which lies in the same plane as the two wires, the direction of the two magnetic fields are the same at any point which does not lie between the two wires. Therefore, the magnetic field outside of the two wires is equal to the sum of the individual magnetic fields (each field calculated using equation 1) and has the same direction as the individual magnetic fields. For example, two wires spaced 5 cm apart and a 10 A current in each wire produce a magnetic field strength of 0.5 nT at a point which is 8 Km from one of the wires.

At a point of interest which does not lie in the same plane as the two wires, the magnetic field strength at any point is calculated by:

$$B = (B_1^2 + B_2^2)^{1/2} \tag{4}$$

where, $B$ = magnetic field strength at the point of interest, T

$B_1$ = magnetic field strength from one wire, T

$B_2$ = magnetic field strength from the other wire, T

and $B_1$ and $B_2$ are calculated by taking into account the magnetic field components in the direction of the point of interest from each wire. For example, two wires spaced 5 cm apart and a 10 A current in each wire produce a magnetic field strength of 0.5 nT at a point which is in another plane and is 8 Km from both wires.

## OTHER MAGNETIC SOURCES

Other sources of magnetic fields are solenoids and toroids. The magnetic field outside of a solenoid is negligible and the magnetic field is inside of a toroid. Therefore, these sources of magnetic fields do not add any significant magnetic interference problems.

## SECTION 4

## SUPPRESSION OR ELIMINATION OF MAGNETIC FIELDS

### GENERAL

This section presents some methods to suppress or eliminate magnetic fields. The three methods presented are shielding, cancellation of sources, and isolation.

### SHIELDING

Shielding is the removal of unwanted energy via the insertion of a metallic barrier between the transmission of such energy and the volume to be protected. To be effective, the shield must consist of a complete enclosure. Some insight into effective shielding is presented.

When there is a great difference in the impedance of the incident wave and the shielding barrier, reflection at the boundary is significant and good shielding can be obtained. This will occur with a low-impedance wave relative to the barrier impedance. For low-impedance or magnetic waves the reflection loss is calculated by:

$$R = 20\ \log_{10}[(0.462/r)(\mu/fG)^{1/2} + 0.136r(GF/\mu)^{1/2} + 0.354] \qquad (5)$$

where, R = the attenuation due to reflection phenomena, dB

r = seperation distance from source to barrier, inches

$\mu$ = magnetic permeability of material relative to vacuum ($\mu$= 1)

f = frequency, Hz

G = conductivity, relative to copper (Cu = 1)

As an example, for copper shielding at a separation distance of 1 inch and at a frequency of 100 Hz; R (reflection attenuation) is 4.9 dB. It can be seen from equation 5 that as the seperation distance is increased, the reflection attentuation also increases and as the frequency decreases, the reflection attenuation also decreases.

While the above equation shows a theoretical value of reflection attenuation from magnetic materials which can be quite high, in practice such levels are rarely achieved particularly at low frequencies. Some of the best results have been obtained by the use of multiple permalloy sheets or the Netic and Co-netic foils. These latter products are available in a variety of ready made forms and sizes to fit diverse applications.

Table 3 summarizes the absorption loss of a number of different materials which may be used for shielding. The loss is given in dB per mil thickness of the metal. The high permeability ($\mu$ = 80,000) materials shown are especially useful for their low-frequency, magnetic field shielding properties.

TABLE 3

CHARACTERISTICS OF METALS USED FOR SHIELDING

| Metal | Relative Conductivity [a] | Relative Permeability | Absorption Loss (dB per mil) 100Hz | 10KHz | 1MHz |
|---|---|---|---|---|---|
| Silver | 1.05 | 1 | 0.03 | 0.34 | 3.40 |
| Copper-Annealed | 1.00 | 1 | 0.03 | 0.33 | 3.33 |
| Copper-Hard Drawn | 0.97 | 1 | 0.03 | 0.32 | 3.25 |
| Gold | 0.70 | 1 | 0.03 | 0.28 | 2.78 |
| Aluminum | 0.61 | 1 | 0.03 | 0.26 | 2.60 |
| Magnesium | 0.38 | 1 | 0.02 | 0.20 | 2.04 |
| Zinc | 0.29 | 1 | 0.02 | 0.17 | 1.70 |
| Brass | 0.26 | 1 | 0.02 | 0.17 | 1.70 |
| Cadmium | 0.23 | 1 | 0.02 | 0.16 | 1.60 |
| Nickel | 0.20 | 1 | 0.01 | 0.15 | 1.49 |
| Bronze | 0.18 | 1 | 0.01 | 0.14 | 1.42 |
| Iron | 0.17 | 1,000 | 0.44 | 4.36 | 43.6 |
| Tin | 0.15 | 1 | 0.01 | 0.13 | 1.29 |
| Steel (SAE 1045) | 0.10 | 1,000 | 0.33 | 3.32 | 33.2 |
| Beryllium | 0.10 | 1 | 0.01 | 0.11 | 1.06 |
| Lead | 0.08 | 1 | 0.01 | 0.09 | 0.93 |
| Hypernick | 0.06 | 80,000 | 2.28 | 22.8 | 228 |
| Monel | 0.04 | 1 | 0.01 | 0.07 | 0.67 |
| Mu-Metal | 0.03 | 80,000 | 1.63 | 16.3 | 163 |
| Permalloy | 0.03 | 80,000 | 1.63 | 16.3 | 163 |
| Stainless Steel | 0.02 | 1,000 | 0.15 | 1.47 | 14.7 |

[a] Relative to Copper.

Shielding efficiency is the sum of the reflection loss and the absorption loss. Magnetic fields are difficult to shield because the reflection loss may approach zero with certain combinations of materials and frequency. With decreasing frequency, the reflection and absorption losses of non-magnetic materials such as aluminum decrease. Consequently, it is difficult to shield against magnetic fields using non-magnetic materials.

The selection of materials for an enclosure as suggested previously is not the end of the enclosure construction problem. There are many other considerations for the efficient development and utilization of enclosures. Two of these considerations are the integrity of joints and penetrations. If not properly implemented, these considerations will negate the shield material as an effective barrier.

The key to obtaining an effective mating joint is the shield material. What is required is a joint that displays the same intrinsic properties (the same values of conductivity and permeability as the shield material) of the shield material throughout the joint. Figure 2 shows a joint that is used by a leading enclosure manufacturer.

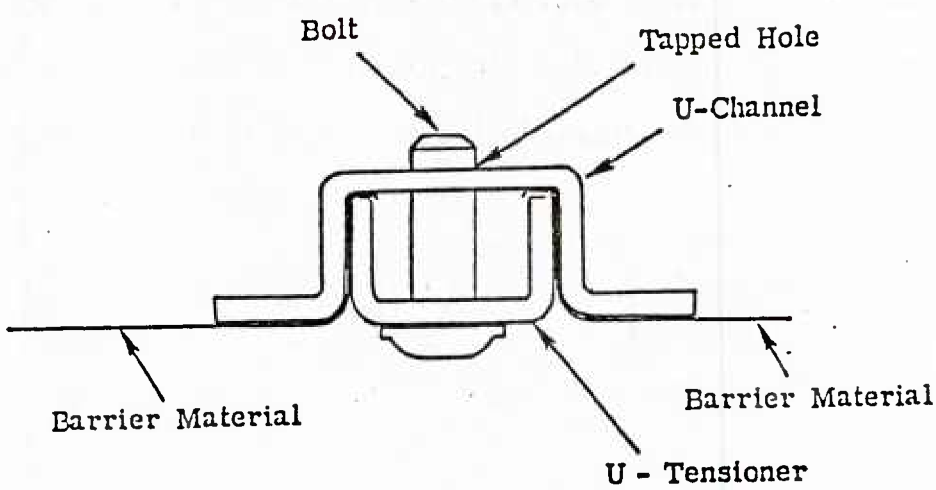


Figure 2. Typical Joint Structure.

It provides the necessary continuity throughout the joint. This joint, due to the tension in the barrier panels generated by the careful tightening of the tensioner, provides good continuity of the inherent material properties. The contact provided by this joint assures a good conductivity across the joint and the large area of contact fulfills the requirement for a low-reluctance path that is necessary for magnetic shielding.

Other methods exist to join panels together. Figure 3 shows several seam configurations. The perferred seam, particularly where the best shielded integrity is required, is a continuous weld around the periphery of the mating surfaces. The type of weld is not critical provided the weld is continuous.

Another requirement for this type of weld is that the filler be of the same basic material as the shield panels. This form of construction does not permit the enclosure to be disassembled and reassembled easily.

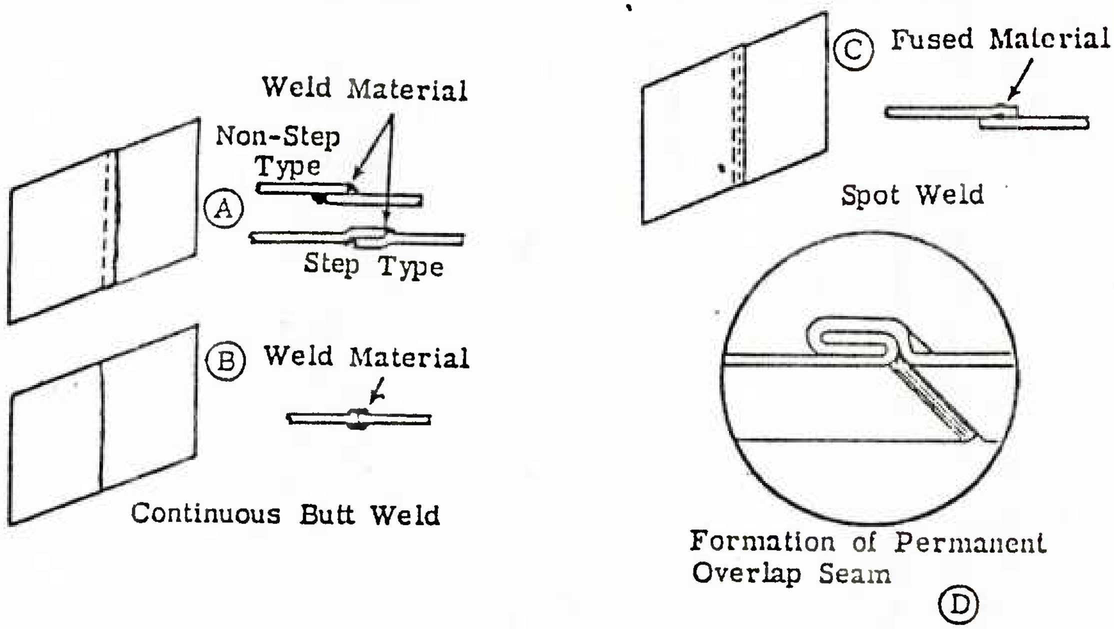


Figure 3. Typical Enclosure Panel Seam Configurations.

Spot welding is another technique used in enclosure construction. Leakage problems stem from improperly bonded seams and seam slits. These often result from gaps in panel members between the spot welds (or other poorly-spaced fasteners such as screws, rivets, or bolts). To reduce this problem to an acceptable level, the spot weld joints should be less than two inches apart.

A crimp seam as shown in Figure 3 is used on a number of small enclosure applications. Strong and lasting crimping pressure should be used. This is assured by spot welding across the seam interface.

The last major problem of constructing the enclosure is the type of penetrations that are utilized. Every enclosure must have provisions for the required power and signal feed-throughs. A number of adequate connectors are available commercially which provide the necessary continuity through the barrier, and the isolation of signal leads that must be obtained for the power and signal feed-through requirements.

The following listing of manufacturers of shielded enclosures is provided in order to obtain more information.

1. ACE Shielded Products Corp., 60 Tomlinson Road, Huntingdon Valley, PA., 19006.
2. Anechoic Systems, 1444 Daisy Ave., Long Beach, California 90813.
3. Cal-Metex Corp., 509 S. Hindry Ave., Inglewood, Calif. 90301.
4. Emerson & Cuming, Inc., Canton, Mass.
5. Filtron Co., Inc., 131-15 Fowler Ave., Flushing, N.Y. 11355.
6. Goodrich, B.F. , Sponge Products Div., EBE-4 Microwave Plant 4, Shelton, Conn., 06484.
7. Hopkins Engineering Co., 129000 Foothill Blvd., San Fernando, Calif., 91342.

8. Lectromagnetics, Inc., 6056 W. Jeff. Blvd., L.A., Calif. 90016.

9. Lindgren, Erik A. & Associates, Inc., 4515 N. Ravenswood Ave., Chicago, Ill., 60640.

10. Magnetic Shield Div., Perfection Mica. Co., 740 Thomas Drive, Bennsenville, Ill., 60106.

11. Metex Corp., 970 New Durham Road, Edison, New Jersey, 08817.

12. Pneumafil Corp., P.O. Box 8009, 2516 Wilkinson Blvd., Charlotte, North Carolina, 28208.

13. RFI Shield-Rooms, P.O. Box 260, Menlo Park, Calif., 94025.

14. Technical Wire Products, Inc., 128 Dermody St., Cranford, New Jersey, 07016.

15. Ray roof Corp., 50 Keeler Ave., Norwalk, Conn., 06856.

16. Trylon, Inc., Elverson, Pa., 19520.

## CANCELLATION OF SOURCES

Cancellation of magnetic fields is another technique used to suppress or eliminate magnetic interference. This technique is possible because magnetic fields of equal magnitude but opposite in direction cancel each other.

As mentioned previously, two parallel current carrying wires under certain conditions produce no magnetic field. The use of twisted-pairs of wires will greatly reduce magnetic interference due to wiring.

Also, the placement of magnets can be used to cancel unwanted magnetic fields. This method is very useful in situations where an isolated module is located and the magnetic field cannot be suppressed or eliminated by any other technique.

## ISOLATION

Isolation of magnetic fields is possible by physical separation. Physical separation can be accomplished on spacecraft by use of an extendable boom. A non-magnetic boom should be used to place the magnetometer sensors at a sufficiently remote distance from the spacecraft.

Many spacecraft used for magnetic measurements have previously used a boom to achieve physical separation of the spacecraft and the magnetometer sensors. Table 4 is a list of some of these spacecraft including the measurment range, quantization, spacecraft field, and boom length employed. The quantization is the intrinsic digitization uncertainty associated with the experiment, spacecraft telemetry system, and ground data processing. The spacecraft field is the net spacecraft field at the sensor position.

TABLE 4

UTILIZATION OF BOOMS ON SPACECRAFT

| Spacecraft | Launch Date (M/D/Y) | Range (gamma) | Quantization (gamma) | Spacecraft Field (gamma) | Boom Length (meter) |
|---|---|---|---|---|---|
| Explorer 10 | 3/25/61 | 3-10,000 | 0.05 | ±1 | 0.8 |
| Explorer 12 | 8/15/61 | ±1,000 | ±12 | 11 | 0.9 |
| Explorer 14 | 10/2/62 | ±500 | ±5 | 17 | 0.9 |
| Explorer 15 | 10/27/62 | ±2000 | ±20 | 4 | 0.9 |
| Explorer 26 | 12/21/64 | ±2000 | ±20 | 3 | 0.9 |
| Pioneer 6 | 12/16/65 | ±64 | ±0.25 | 0.3 | 2 |
| Explorer 33 | 7/1/66 | ±64 | ±0.25 | 0.2 | 2 |
| Pioneer 7 | 8/17/66 | ±32 | ±0.125 | 0.2 | 2 |
| Explorer 34 | 5/24/67 | ±32 | ±0.16 | 0.3 | 2 |
| Explorer 35 | 7/19/67 | ±60 | ±0.6 | 0.2 | 2 |
| Pioneer 8 | 12/13/67 | ±32 | ±0.125 | 0.2 | 2 |
| Pioneer 9 | 11/8/68 | ±200 | ±0.2 | ±0.5 | 2 |

## SECTION 5

## SUMMARY AND RECOMMENDATIONS

### SUMMARY OF MAGNETIC SOURCES OF SPARTAN

The following is a summary of major magnetic sources of Spartan. A general indication of the magnitude of each magnetic source is also provided.

1. Batteries - The batteries generate a magnetic field at a distance of 30 cm of less than 1 nT. The physical location of the batteries with respect to the experiment location is sufficient to protect the magnetometer from this magnetic source.

2. Tape Recorder - The typical magnetic field strength of a tape recorder head is 0.65 to 0.82 T. Some method to suppress or eliminate this magnetic source is required.

3. Data Control Electronics and ACS - Measurements from the sounding rocket program indicate magnetic dipole moments of 91.97 kT/m$^3$ in the X direction, 68.23 kT/m$^3$ in the Y direction, and 54.15 kT/m$^3$ in the Z direction. The data also indicates the largest magnitude of the magnetic

field in each direction to be 289.8 nT in the X direction, 476.8 nT in the Y direction, and 202.6 nT in the Z direction. These measurement results should be similar to those for Spartan. Some method to suppress these fields is required to meet the magnetometer sensitivity requirement (less than 1 nT).

4. Wiring - Any wire carrying current produces a magnetic field. Of the wiring configurations analyzed in this report, 80 m to 8 Km separation may be required between Spartan and the magnetometer (based on maximum current of 10 A supplied by Spartan). Again, some method to suppress the magnetic fields from wires is required.

## RECOMMENDATIONS

The Spartan 2 is scheduled for magnetic calibration measurements in early Spring 1985. It is recommended that these measurements be used to determine the extent of protection required for the magnetometer from Spartan.

Use of an extendable/retractable boom is required to meet the magnetometer sensitivity requirement due to the inefficiency of shielding against low-frequency magnetic fields. Shielding will be required to reduce the magnetic field levels from the tape recorder, data control electronics, and ACS in order to minimize the length of the boom. Use of twisted-pairs of wires, where practical, is recommended to minimize the magnetic field levels generated by wiring.

# Appendix C: Introductory Survey of Satellite Ground Tracking System for the Spartan/ Magnetometer Experiment OAO Corp.

# INTRODUCTORY SURVEY OF SATELLITE GROUND TRACKING SYSTEMS FOR THE SPARTAN/MAGNETOMETER EXPERIMENT

September 1984

Prepared for
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

In Response to
Contract NAS 5-28057, Task 7

Prepared by
OAO Corporation
7500 Greenway Center Drive
Greenbelt, Maryland 20770

Under Subcontract 7267, Task 2 to
ORI, Inc.
1375 Piccard Drive
Rockville, Maryland 20850

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OAO CORPORATION

# SECTION 1. INTRODUCTION/BACKGROUND

# SECTION 1. INTRODUCTION/BACKGROUND

The Navy has a continuing requirement to map the Earth's magnetic fields, primarily of the ocean areas, to a high degree of accuracy. To meet this requirement for accurate, up-to date magnetic charts the Naval Ocean Research and Development Activity (NORDA) is researching the possibility of installing a magnetometer system on a NASA Spartan carrier to perform these measurements from space. It is believed that this approach could provide a more accurate, relatively low cost method of obtaining magnetic field measurements of the ocean areas. Current planning is for the Spartan/Magnetometer Mission to be available for a shuttle launch in the 1988-89 time period.

The NASA Spartan carrier is presently designed to accommodate sounding rocket type payloads for periods up to several days. The carrier will be deployed and operated from a space shuttle as an autonomous sub-satellite. Upon the mission completion the Spartan will be retrieved by the shuttle and returned to the ground for reuse.

The report is divided into the following sections. Section 2 is the task objective, while Section 3 covers the methodology used to perform this introductory survey. Section 4 provides a brief discussion of the tracking systems that were surveyed, while Section 5 presents the pros and cons for each system for this magnetic field mapping application. Section 6 contains the conclusion and recommendation of the OAO survey team.

# SECTION 2. TASK OBJECTIVE

# SECTION 2. TASK OBJECTIVE

The purpose of this task by OAO Corporation is to provide an introductory (Pre-Phase A) survey of the various navigational methods (systems) that could provide precision satellite tracking, both active and passive, that would be available in the 1987-1997 time period. NORDA requires that the satellite navigation method must be capable of providing a ground track accuracy of 50 meters or better (either in real-time or by post-flight analysis) on the Spartan/Magnetometer system acquired data. In addition, OAO is to explore methods for generating time tagging of the onboard recorded magnetometer data to achieve measurement and location correlation. It is also NORDA's desire to acquire this satellite magnetometer mapping and tracking capability at the lowest cost possible.

# SECTION 3. METHODOLOGY

# SECTION 3. METHODOLOGY

The first step of this introductory survey was to perform a documentation search, through the NASA and OAO libraries, on all current and future navigational tracking systems reports and user guides. This was followed by informal discussion with NASA/GSFC and OAO personnel cognizant of navigation systems and methods. OAO also participated in a Spartan/Magnetometer Project status meeting on August 16, 1984.

The information obtained from this survey was then synthesized, based on NORDA's requirements, and the results and OAO's recommendations are documented in this report.

# SECTION 4. NAVIGATIONAL TRACKING SYSTEMS (METHODS) CONSIDERED

# SECTION 4. NAVIGATIONAL SYSTEMS (METHODS) CONSIDERED

## 4.1 INTRODUCTION

Normally, orbit determination techniques are broken down into the following categories:

a. Data acquisition systems or measurements (such as radar, Doppler, interferometry, laser, etc.);

b. Dynamic models (such as gravity, atmospheric drag, etc.); and

c. Computational techniques which include trajectory propagation considerations (general and special perturbations) and estimation techniques (batch and sequential processing).

However, the essential feature that highlights orbit determination from other aspects of orbital mechanics is the use of measurement data from which the trajectory state is derived. Therefore, this survey, due to the funding limitation, dealt primarily with the data systems or measurement category.

## 4.2 SELECTION CRITERIA

OAO used four general criteria for selecting the primary navigational data (measurement) system for further review. These criteria were:

a. Ability of system to provide near worldwide, continuous coverage (independent of limitations imposed by the shuttle orbit configuration and duration of flights);

b. Possibility of system meeting the 50 meter or better ground tracking requirement;

c. Potential for the system to be in successful operation in the late 1980's; and,

d. System/method must be reasonably uncomplicated, practical and relatively low cost.

## 4.3 NAVIGATION SYSTEMS

Based upon the above listed criteria OAO concentrated their efforts on three primary data (measurement) systems. These were the NASA Spaceflight Tracking and Data Networks (STDN) with the Tracking and Data Relay Satellite System (TDRSS), DOD's Global Positioning System (GPS), and the Smithsonian Astrophysical Observatory (SAO) laser tracking system.

### 4.3.1 SPACEFLIGHT TRACKING AND DATA NETWORK (STDN) WITH TRACKING AND DATA RELAY SATELLITE SYSTEM (TDRSS)

The current NASA Spaceflight Tracking and Data Network (STDN) consists of a ground segment made up of fourteen ground stations called the Ground Spaceflight Tracking and Data Network (GSTDN), and a space segment known as the Tracking and Data Relay Satellite System (TDRSS).

4.3.1.1 Ground Spaceflight Tracking and Data Network. The GSTDN with its fourteen ground stations currently provides the majority of the telemetry, tracking, and command satellite support. Eventually, as TDRSS proves it can provide this full capability, NASA plans to phase-down GSTDN to a core network to be used only for supporting highly elliptical and geosynchronous satellites, along with launch and landing support. The prime GSTDN ground stations, when the phase down is complete, will be located at Goldstone, California; Madrid, Spain, and Orroral Valley, Australia.

4.3.1.2 Tracking and Data Relay Satellite System (TDRSS). The TDRSS currently consists of one satellite, but when fully operational, will consist of a ground station at White Sands, New Mexico and two operational Tracking and Data Relay Satellites (TDRS) located in geosynchronous orbits at 41 degrees and 171 degrees west longitude. The system will also include an in-orbit spare satellite, and the capability for a fourth satellite to be ready for a rapid launch replacement should an orbit failure occur.

TDRSS can provide user and TDRS tracking data for user orbit determination. TDRS tracking data will be obtained by scheduling tracking services to NASA ground-based transponders. TDRS tracking data will be used only by the NASA/GSFC Operations Supporting Computing facility in determining user orbits. Error analysis has shown that, for orbit maintenance, one TDRS is capable of tracking and navigating user spacecraft to the same accuracy as the existing GSTDN. A comparison of the existing GSTDN with TDRSS for long-arc tracking is presented in Table 4-1.

Table 4-1. TDRSS Versus Existing GSTDN for Long Data Arcs (note 1)

| User Orbit | Position Uncertainty (meters) | |
|---|---|---|
| | GSTDN (note 2) | TDRSS (note 3) |
| 910 x 910 km, i-99$^{0}$ | 59 | 60 |
| 435 x 435 km, i-50$^{0}$ | 730 | 720 |

Note

1. Assumes TDRS 150-meter position uncertainty.
2. USB tracking.
3. Assumes bilateration tracking of TDRS.

The TDRSS tracking scenario is described in Figure 4-1. Each of the Tracking and Data Relay Satellites will move in a slender figure-eight-shaped orbit referenced to rotating-earth coordinates.

User satellite range measured by TDRSS is the sum of the ground terminal-to-TDRS path length ($R_1$) and the TDRS-to-user satellite path length ($R_2$) as shown. The computational support to provide tracking and positional data to develop position/sensor measurement information utilizes an extensive computational scheme and is available through GSFC's Operational Supporting Computing facility.

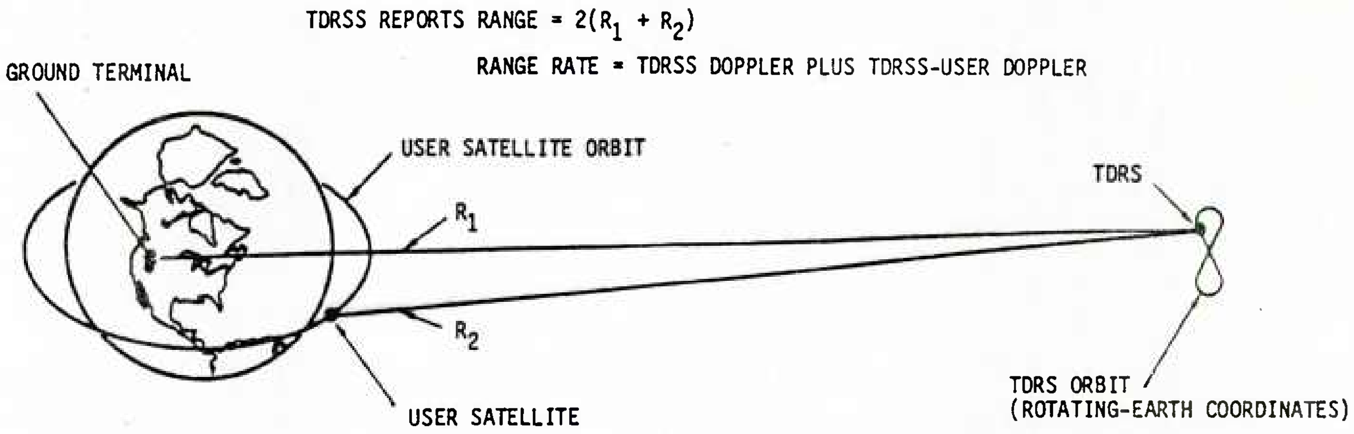


Figure 4-1. TDRSS Tracking Geometry

### 4.3.2 SMITHSONIAN ASTROPHYSICAL OBSERVATORY (SAO) LASER TRACKING NETWORK

The Smithsonian Astrophysical Observatory (SAO) laser tracking system consists of ten tracking stations worldwide. The SAO is currently a research program involving lasers to track selected satellite systems (i.e. BE-C, GOES 1 and 3, Starlette, and LAGEOS) which incorporate cube-corner reflectors.

The current network does not provide contiguous, global coverage and is unlikely to be an operational system within the next several years. The system is capable of extremely accurate range tracking to within 5-10 cm, but requires complex data gathering and processing techniques to obtain usable satellite ground tracks. In addition, the lack of a time tagging system also complicates its use in providing a reasonable method for tracking a satellite system.

4.3.3 GLOBAL POSITIONING SYSTEM (GPS)

The GPS is a space-based radio positioning, navigation and time-transfer system that operates on two L-band frequencies, 1575.42 MHz ($L_1$), and 1227.6 MHz ($L_2$). The GPS will comprise three major segments: Space, Control, and User.

4.3.3.1 Space Segment. The GPS space segment, when fully operational (scheduled to be 1989), will consist of 18 satellites in six orbital planes, with three satellites appropriately spaced in each plane. The satellites will operate in circular 20,200 km orbits at an inclination angle of 55 degrees and with a 12-hour period. The precise spacing of satellites in orbit will be arranged so a minimum of four satellites will be in view to a user at all times, thereby ensuring worldwide coverage. Each satellite will transmit an $L_1$ and $L_2$ signal. $L_1$ will carry a precise signal and a clear/acquisition signal. $L_2$ will carry either a precise or a clear/acquisition signal. Superimposed on these signals will be navigation and system data including satellite ephemeris, atmospheric propagation correction data, and satellite clock bias information.

4.3.3.2 Control Segment. The control segment will include a number of monitor stations and ground antennas located throughout the world. The monitor stations will use a GPS receiver to passively track all GPS satellites in view and thus accumulate ranging data from the GPS satellite signals. The information from the monitor stations will be processed at the master control station to determine GPS satellite orbits and to update the navigation message of each satellite. This updated information will be transmitted to the satellites via ground antennas, which also will be used for transmitting and receiving satellite control information.

4.3.3.3 User Segment. The user segment will consist of User Equipment Sets, test instrumentation and peculiar support equipment. The User Equipment Set, utilizing data transmitted by the GPS satellites, will derive navigation and time information for use in the user vehicle

(satellite). The user satellite receives pulses emitted from multiple GPS satellites and the onbord computer computes the position of the user satellite in terms of latitude, longitude, and altitude above the earth's surface. The navigational accuracy anticipated from the GPS is approximately 5 to 10 meters. Thus, in the case of the Spartan/Magnetometer application, an onboard tape recorder can record positional information directly, and without further computation the ground track location of the magnetic measurement has been taken.

# SECTION 5. PROS AND CONS OF TRACKING SYSTEMS

# SECTION 5. PROS AND CONS OF TRACKING SYSTEMS

## 5.1 GENERAL COMMENTS

The currently used NASA satellite tracking (i.e. STDN/GSTDN) system is costly to use because:

a. Multiple ground stations must produce time correlated position/tracking information;

b. Time correlated tracking data requires additional (extensive) computation to calculate precision positional information of satellite (sensor) - accuracy is approximately 730 m at lower altitudes (reference Table 4-1);

c. Using time annotated measurements from satellites requires time correlation with precision position data - this entails a significant computational effort.

Listed below are comments about each of the tracking systems. These comments are correlated to the survey criteria specified by OAO in Section 4.2 of this report.

## 5.2 STDN/GSTDN

Criteria comments:

a. Reasonably continuous world coverage;

b. Does not meet 50 m or better tracking requirement;

c. System is being phased down and eventually TDRSS will provide tracking data;

d. Requires Spartan carrier to have STDN/GSTDN transponder to facilitate tracking. Ground segment, is complex and requires extensive computational support - Very costly and requires highly accurate spacecraft clock.

## 5.3 STDN/TDRSS

Criteria Comments:

a. Reasonable continuous worldwide coverage;

b. Does not meet 50 m or better ground tracking requirement;

c. High potential to be operational in late 1980's;

d. Requires Spartan carrier to have a TDRSS Transponder. Likely difficulties when tracking and will require more than one TDRSS satellite to be used to provide (a) above. Ground segment considerations are similar to STDN/GSTDN. Therefore very costly to operate. Also requires accurate spacecraft clock.

## 5.4 SAO LASER TRACKING

Criteria Comments:

a. Limited tracking coverage of the world;

b. Can provide a much better (5-15 cm) tracking capability than the required 50 m;

c. System is only experimental with questionable availability in the late 1980's;

d. Contrary to STDN (GSTDN and TDRSS) the Spartan carrier does not need to carry active transponder. Requires retro-reflectors to be carried by Spartan which must remain pointed toward earth. Ground segment is complex and space laser trackers are still more or less experimental; costly to operate and maintain. Ground computational support appears to be extensive and costly. Computational system is not operational but experimental in character. Also requires highly accurate spacecraft clocks.

## 5.5 GPS

Criteria Comments:

a. Reasonably continuous worldwide coverage;

b. Meets and/or exceeds 50 m tracking requirement;

c. Fully operational system will be in operation by the late 1980's;

d. Due to large user base and substantial investment by DOD, GPS receivers will be readily available, be of high quality, and be reasonably priced. Receivers will provide direct positional read out, spacecraft velocity and precise time (no spacecraft clock required). This indicates that ground computational support required is near nil, and has the added advantage of space acquired data (measurement) being properly correlated with ground track data.

## 5.6 COMPARISON OF ON-BOARD NAVIGATION BETWEEN GPS AND TDRSS

Table 5-1 compares the on-board navigation of GPS vs. TDRSS showing some advantages and disadvantages of each system.

Table 5-1. GPS vs TDRSS for On-board Navigation

| FEATURES | GPS | TDRSS |
|---|---|---|
| ONBOARD HARDWARE REQUIREMENTS | ANTENNA, RECEIVER, CLOCK, FREQUENCY STANDARD, RANGE AND RANGE DIFFERENCE EXTRACTOR, NAVIGATION COMPUTER, FREQUENCY SYNTHESIZER | DOPPLER EXTRACTOR, SYNTHESIZER, NAVIGATION COMPUTER |
| REALTIME ACCURACY | 5-10m | 50-100m (high altitude)<br>720m (low altitude) |
| ADVANTAGES | RAPID STATE VECTOR RECOVERY (MANEUVERING VEHICLES) (2.3 MIN. ), HIGH ACCURACY, KEEPS ACCURATE ONBOARD TIME, GLOBAL COVERAGE | LOW INCREASE IN POWER, WEIGHT, SPACE. NO ADDITIONAL ANTENNA, RECEIVER, CLOCK, OR FREQUENCY STANDARD REQUIRED, SIMPLIFIES ACQUISITION PROCEDURES AT WHITE SANDS (NO FORWARD COMPENSATION REQUIRED) |
| DISADVANTAGES | ADDITIONAL EQUIPMENT INCREASE POWER, WEIGHT, SPACE, APPENDAGES. POSSIBLE DENIAL OF ACCURACY TIED TO DOD NEEDS | LESS ACCURATE: LONGER STATE RECOVERY TIMES (SEVERAL HOURS), TIME MAINTENANCE MUST BE EXTERNAL, SPARCE TRACKING COVERAGE |

## SECTION 6. CONCLUSIONS AND RECOMMENDATIONS

## SECTION 6. CONCLUSIONS AND RECOMMENDATIONS

Due to the advantages (superior performance, low cost, etc.) of the GPS system its selections as candidate for the Spartan application is obvious.

Based on the result of this study the following recommendations are made:

a. Examine and assess the performance characteristics and costs of the Landsat 4 and 5 GPS receiving system (GPSPAC) currently being used in space.

b. Develop a conceptual design for the integration of a GPS receiving system into the current design of the Spartan carrier.

c. Assess the operational and cost impact of the GPS approach on the Spartan/Magnetometer mission. Include a detailed cost trade-off study.

d. OAO Corporation with its several years of unique experience and participation in the GPS program, would make a logical choice to perform these follow-on studies.

# SECTION 7. GLOSSARY

## SECTION 7. GLOSSARY

DOD - Department of Defense

GPS - Global Positioning System

GPSPAC - First experimental spaceborne/GPS navigation set

GSTDN - Ground Spaceflight Tracking and Data Network; ground segment of STDN.

NORDA - Naval Ocean Research and Development Activity

SAO - Smithsonian Astrophysical Observatory

STDN - Spaceflight Tracking and Data Network

TDRS - Tracking and Data Relay Satellite

TDRSS - Tracking and Data Relay Satellite System; space segment of STDN

# Appendix D: NAVOCEANO Letter Establishing Project MAGNET Baseline Cost

DEPARTMENT OF THE NAVY

U.S. NAVAL OCEANOGRAPHIC OFFICE

NSTL STATION

BAY ST. LOUIS, MISSISSIPPI 39522

IN REPLY REFER TO

Ser 8200/5665

3140

5 MAR 1984

From: Commanding Officer, Naval Oceanographic Office

To: Commanding Officer, Naval Ocean Research and Development Activity

Subj: Cost baseline data for conducting Project MAGNET aeromagnetic surveys

Ref: (a) NORDA ltr ser 370/607 of 6 Feb 84

1. In response to reference (a), the following estimates of cost baseline measurements for conducting aeromagnetic vector surveys are provided. These estimates are broken down into aircraft operating costs and Naval Oceanographic Office (NAVOCEANO) costs. The original cost of the RP-3D aircraft in 1970 was \$6.7M with an additional \$3.3M for modifications for a total unit cost of \$10.0M. Delivery of the RP-3D was in 1971 with a projected service life of 28 years. Under certain circumstances this life cycle can be extended an additional 12 years. Aircraft operating costs both direct and indirect are \$2.8M. Total annual cost for aircraft operations are computed as follows:

| RP-3D aircraft | Unit Cost ($M) | Years of Service Life | Projected Annual Cost ($M) | Operating Cost ($M) | Total Annual Cost ($M) |
|---|---|---|---|---|---|
| | 10.0 | 28 | 0.357 | 2.8 | 3.157 |

NAVOCEANO's current operating funds specifically targeted for aeromagnetic surveying is \$0.887M. Total annual cost for the vector program is \$4.04M. Data acquisition is programmed at 240,000 track miles per year. Annual data processing costs, which are not included in the previous figures, are \$0.246M.

J. M. SEARS

Copy to:
COMNAVOCEANCOM

# Appendix E: NASA/HQ Letter Establishing Spartan as Primary Payload

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

AUG 27 1984

Reply to Attn of: MC

Mr. Don L. Durham
Naval Ocean Research and Development Activity
Department of the Navy
Department of Defense
NSTL, MS 39529

Dear Mr. Durham:

My staff has reviewed your correspondence of July 13, 1984, requesting cost estimates for Spartan free-flyer as a Shuttle payload. Based on that review, I have forwarded your inquiry to the Johnson Space Center for their development of the authoritative cost estimates which you require since the Spartan, as a free flyer with retrieval, will be in the class of a primary payload.

The cost estimates which the Johnson Space Center will be able to provide will be those for the standard services associated with launching the payload and any optional services costs which may be required to effect the rendezvous/retrieval of the Spartan spacecraft and to establish the mission timeline and Orbiter configuration to support the retrieval.

Regarding the estimates provided to you by the Goddard Space Flight Center, inasmuch as these estimates are all related to cargo elements and preparation of the Spartan spacecraft and its support equipment for reflight, this office is not really in a position to offer an authoritative assessment of the validity of the Goddard projections of costs or lead times. I do know, however, that the people at Goddard have extensive experience in performing the kinds of spacecraft preparation tasks which are described, and I would tend to have confidence in the soundness of their estimates.

Should you require any additional detailed information, please feel free to pursue your inquiries directly with the Johnson Space Center through the USAF Headquarters Space Division. The Air Force has been designated by the Department of Defense to serve as the Executive Agent for all matters related to mission planning and the actual integration of DOD payloads with the Shuttle. The responsible individual at Space Division is Brig. General Donald L. Cromer, Deputy Commander for Launch and Control Systems.

I look forward to hearing more about the Spartan free-flyer on the Shuttle. If there are any matters in which we can support your efforts directly as your planning progresses, please let me know.

Sincerely,

Jesse W. Moore
Associate Administrator
for Space Flight

# Appendix F: NASA/JSC Establishing Launch Cost

National Aeronautics and
Space Administration

**Lyndon B. Johnson Space Center**
Houston, Texas
77058

NASA

Reply to Attn of: LP/84-L612

JAN 0 2 1985

Mr. Don L. Durham
Dept. of the Navy
Naval Ocean Research and
Development Activity (NORDA)
NSTL, MS 39529

Dear Mr. Durham:

At the request of Mr. C. M. Lee, Director, Customer Services Division, NASA Headquarters, I am enclosing a copy of the Preliminary Price Summary for Spartan, updated to reflect our understanding of NORDA requirements at this time. It should be noted that the pricing summary is only an estimate and includes Shuttle launch costs and associated optional services charges for payload integration. The estimates are in FY 82 dollars and billings will be escalated to date of payment.

If we can be of any further assistance, please contact Mr. Wayne Eaton at (713) 483-5923.

Leonard S Nicholson 1/2/85

Leonard S. Nicholson
Manager, Mission Integration
National STS Program Office

Enclosure

cc:
NASA Hqs., MC/J. M. Moore
NASA Hqs., MC/C. M. Lee

STS PRELIMINARY PRICE SUMMARY
PRICE PER LAUNCH — CURRENT YEAR DOLLAR ESTIMATES*

DATE PREPARED: 12/10/84

PAYLOAD IDENTIFICATION: SPARTAN (EOP) TYPE LAUNCH

| | ESTIMATE* | USE FEE |
|---|---|---|
| STANDARD SHUTTLE PRICE ($M): | 8.632 | 0 |
| OPTIONAL FLIGHT SYSTEM PRICE ($M): | 0 | 0 |
| OPTIONAL SERVICE PRICE ($M): | 2.114 | 0 |
| TOTAL ESTIMATED PRICE ($M): | 10.746 | 0 |

STANDARD SHUTTLE CHARGE INFORMATION

PAYLOAD CHARGEABLE WEIGHT (LB): 4500, LENGTH (IN.): 66

INCLINATION: 28.5 DEG, CHARGE FACTOR: .122

EARNEST MONEY DATE: , LAUNCH DATE:

NUMBER OF FLIGHTS IN SERIES: 1

B.L.S. INDEX FACTOR*: 1.862 AS OF: 04/01/82

STANDARD: $38.0 (75$M) PLUS USE FEES $

OPTIONAL FLIGHT SYSTEM INFORMATION

NONESCALATING - NOT APPLICABLE

*ESTIMATES SUBJECT TO ESCALATION ACCORDING TO THE BUREAU OF LABOR STATISTICS (B.L.S.) INDEX AS DEFINED IN THE NASA REIMBURSEMENT POLICIES NMI 8610.8 AND NMI 8610.9; USE FEES ARE NOT SUBJECT TO ESCALATION.
!!!NOTICE!!! THESE ESTIMATES ARE IN FY 82 YEAR DOLLARS. THE BILLINGS WILL BE IN FUTURE VALUE DOLLARS!!

## PAYLOAD RELATED OPTIONAL SERVICE INFORMATION

| OPTION DESCRIPTION | ESTIMATE ($M) ($M) |
|---|---|
| NONESCALATING: | |
| N/A | |
| OTHER: | |
| 1. MODIFIED MECHANICAL GRAPPLE FIXTURE | .085 |
| 2. STS WILL PROVIDE THE FOLLOWING CABLES | |
| A. DC POWER CABLE AND CONNECTOR I/F BRACKET | .030 |
| B. AC POWER CABLE FROM PRLA TO THE SIP | .030 |
| 3. STS-PROVIDED OPTIONAL SERVICES | |
| A. MODIFICATION OF VISUAL GRAPHICS FOR THE SMS | .150 |
| B. MODIFICATION OF THE MDF MOCKUP AND USE OF MDF | .050 |
| C. CREW PROCEDURES DEVELOPMENT FOR RENDEZVOUS | .025 |
| D. CREW TRAINING FOR RENDEZVOUS AND PROXIMITY OPERATIONS | .462 |
| E. CREW TRAINING FOR RMS RETRIEVAL | .197 |
| 4. KSC SUPPORT AND USE OF THE PPF | .600 - .900 |
| 5. POSTFLIGHT DATA REQUIREMENTS | |
| A. CCTV/VCR CASSETTE (ONE) | .001 |
| B. ONE SET DUPEPOSITIVE TRANSPARENCIES | .001 |
| 6. CONTINGENCY TRAINING FOR EVA RELEASE OF REM | .128 - .283 |
| OPTIONAL SERVICE SUBTOTAL | 1.759 - 2.114 |